EVALUATION OF ABBREVIATED METHODS FOR ROUTINE SOIL TESTING

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by

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Final Report

EVALUATION OF ABBREVIATED METHODS FOR ROUTINE SOIL TESTING

TO: K. B. Woods, Director
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[illegible] 63

FROM: H. L. Michael, Associate Director
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Project No: C-[illegible]

The attached Final Report [illegible] Evaluation of Abbreviated Methods for Routine Soil Testing [illegible] been submitted by Mr. [illegible] Graduate Assistant on our staff [illegible] the [illegible] of Professor [illegible]. Mr. [illegible] also [illegible] the [illegible] for the [illegible] degree in June 1963.

This study was [illegible] the applicability and reliability of abbreviated [illegible] soil testing. Abbreviated methods for liquid limit, plastic limit [illegible] relationships were found to be reliable [illegible]. The California Bearing Ratio was also studied [illegible] amount of experimental error was found to be present [illegible] prediction of [illegible] value by abbreviated methods very [illegible].

The report is [illegible] for the record.

Respectfully submitted,

[illegible signature]

Harold L. Michael, Secretary

HLM:bc

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Final Report

EVALUATION OF ABBREVIATED METHODS FOR ROUTINE SOIL TESTING

by

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File No: 6-14-7

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ABSTRACT

Wermers, Lyle G. MSCE, Purdue University, June 1963. EVALUATION OF ABBREVIATED METHODS FOR ROUTINE SOIL TESTING. Major Professor: Eldon J. Yoder.

The utilization of soil as an engineering material has necessitated the developement of soil classification systems. Classification is based upon soil properties determined by the performance of standard test procedures. Abbreviations of these standard procedures have been formulated and a study was conducted to determine the applicability of the abbreviated procedures.

A one-point liquid limit method was shown to be reliable and economical. The squash method for determination of the plastic limit was shown to be reliable but to have little affect on the testing cost. A one-point compaction procedure was shown to be reliable and economical.

The California Bearing Ratio was studied and a considerable amount of variability was shown to exist due only to experimental error. This experimental variability was shown to be greatest for granular soils and least for clay soils.

Equations for estimating the optimum moisture content, maximum dry density, and California Bearing Ratio were developed by the multiple regression technique. These

equations were shown to be reliable estimators of the optimum moisture content and maximum dry density but were shown to be of questionable value as estimators of the California Bearing Ratio.

INTRODUCTION

Adequate identification of a material is a prerequisite to the proper utilization of that material. As it pertains to soil engineering, identification is accomplished by performing standard tests.

These standard tests have been rigorously defined by the American Society for Testing Materials (3)* and the American Association of State Highway Officials (2). The time required for the performance of the standard tests has brought about a demand for their abbreviation and efforts have been channeled toward this end by several investigators.

A portion of this thesis is devoted to a study of routine soil testing procedures with the end point of determining whether short cut testing techniques yield adequate soil identification data.

The identification of soil, however, is of use only if it leads to the solution of an engineering problem. A problem of primary interest to the highway engineer is the structural design of pavements. The design procedure used by the Indiana Highway Commission is based in part on the California Bearing Ratio of the subgrade. If a knowledge of the classification properties of the subgrade would yield

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* Numbers in parenthesis refer to references listed in the Bibliography.

this design parameter, a considerable amount of testing could be circumvented. Hence, a study of the relationships which exist between the CBR and the classification properties of soils was performed utilizing the accumulated data of the Joint Highway Research Project laboratory at Purdue University.

Associated with each soil property is a certain amount of variability due only to testing procedure. This variability was considered when appraising the value of the statistically developed prediction formulas for optimum moisture content, maximum dry density, and California Bearing Ratio.

REVIEW OF LITERATURE

Atterberg Limits

Albert Atterberg, (4) a Swedish scientist, performed a study of plasticity of clays in the early 1900's. In the study he defined the "Atterberg limits" much as they are known tody.

In the early 1930's, Arthur Casagrande (6), redefined these limits for engineering purposes and developed the currently utilized liquid limit device. Casagrande's methods and definitions have been adopted widely by the engineering profession.

The increased work load of engineers has brought about a demand for test methods which minimize time requirements. This demand has been partially met by the development of abbreviated procedures for the determination of Atterberg limits.

In 1949, the U. S. Army Corps of Engineers (19) reported on a "one-point" liquid limit method predicated on the hypothesis that geologically similar soils yield the same flow line.

In the early 1950's the U. S. Department of Commerce, Bureau of Public Roads (11) compared the results of a one-point liquid limit test with the results of the standard test. They studied test results from throughout the United States

and concluded that the error associated with the one point method was no greater than that associated with the standard method.

An alternative method for the determination of the plastic limit was reported by Abun-Nur (1). The method consists of "squashing" a cube of wetted soil and determining the moisture content at which cracks develop on the cube surface. A comparison of this method with the standard "roll-out" method showed little difference between results. A similar procedure utilizing a ball of wetted soil was established by Clegg (7) to be quite reliable.

Moisture-Density Relationship of Soils

In 1933 Proctor (14) reported on the principles of soil compaction and outlined procedures for determining the moisture-density relationship of soils. Proctor's principles and procedures have been widely accepted and with few modifications are outlined as standard procedures by the American Association of State Highway Officials (AASHO) (2).

Woods and Litehiser (23), in 1938, presented a set of typical moisture-density curves for Ohio soils. They showed that similar soils have similar moisture-density curves. This characteristic was utilized in the rapid determination of the optimum moisture content and maximum dry density.

Hampton (10) showed a relationship to exist between the plastic limit and the maximum dry density of a material. The Bureau of Public Roads (15) performed a statistical analysis

of compaction and classification test data to arrive at a relationship between these values. They presented prediction formulas which relate optimum moisture content and maximum dry density to the standard classification properties, such as Atterberg limits and grain size distribution.

The Corps of Engineers and Bureau of Public Roads have studied the factors affecting soil compaction in great depth.

California Bearing Ratio

During 1928 and 1929 the California Division of Highways (13) undertook an extensive investigation of pavement failures throughout the state of California. In 1929 a bearing ratio test was devised, the results of which were correlated with pavement performance. This bearing ratio test, which compares the strength of a soil to the strength of a crushed stone, has become known as the California Bearing Ratio or CBR.

During the 1940's the U. S. Army Corps of Engineers (17) adopted the CBR test for pavement design and established the procedures which are normally used today.

Relationship Between Soil Strength and Other Soil Properties

A considerable amount of work has been done to relate soil strength to the classification properties of soils. The U. S. Army Corps of Engineers (20) has shown that a high degree of correlation exists between moisture content and cone index. Woods (22) has shown a direct relationship between penetration resistance and dry density. He also showed an inverse relationship between penetration resistance and the

Atterberg limits. Gawith and Perrin (9) presented a relationship between CBR and grain size distribution and group index. Hampton (10) studied the factors affecting the CBR for low strength soils. He found the variability due to testing to be quite low. The U. S. Army Corps of Engineers (21) has studied extensively the effect of test procedure on CBR values.

A method of estimating the CBR from plasticity data has recently been developed by Black (5) of England. Black related the CBR of a soil to the soil suction and developed the relationship between soil suction and the Atterberg limits.

PURPOSE AND SCOPE

The purposes of this study were twofold. First, the applicability of using abbreviated routine soil testing procedures was determined. Second, formulas for predicting California Bearing Ratio as a function of soil classification properties were developed. A by-product of the CBR study was a determination of the degree of correlation existing among classification properties, optimum moisture content, maximum dry density, and CBR.

The only testing undertaken specifically for this study was a series of CBR tests on three soils. These soils were chosen to represent those normally encountered in the Joint Highway Research Project (JHRP) testing program and consisted of a clay, a silt, and a gravel. The results of this testing permitted an estimate of the variability in the CBR which is due to testing procedures.

All other data used in the evaluation of the abbreviated procedures and in the correlation study were taken from accumulated data of the JHRP laboratory at Purdue University. These data yielded information on soils from the following Indiana Counties:

Allen	Parke
DeKalb	Pulaski
Fountain	Sullivan
Madison	Tippecanoe
Noble	Tipton

There was no consistency in number of samples per county and no attempt was made to separate data on the basis of county.

Hampton (10) found that a considerable amount of the variability in a soil property is attributable to the horizon from which the sample is taken. To eliminate this variable from the prediction models, the data were grouped according to A-, B- or C-horizon. Any soil, irrespective of horizon, which did not display measurable Atterberg limits was also placed in a separate group.

Significance of differences between results of abbreviated and standard procedures were tested. Multiple regression analyses were performed to develop prediction equations for optimum moisture content, maximum dry density, and California Bearing Ratio.

PROCEDURE

This study, as previously noted, consisted of a comparison of alternative test procedures. In every case an abbreviated or revised method was compared with an accepted standard method. This comparison formed the basis for judgment concerning the validity of the abbreviated or revised method.

Atterberg Limits

The standard procedures for the determination of the Atterberg limits are defined by the American Association of State Highway Officials (2). The procedures for determination of the liquid limit, plastic limit, and plasticity index are outlined in AASHO designations T89-60, T90-56, and T91-54 respectively.

The abbreviated liquid limit procedure studied was a "Flow Index" method developed by H. Y. Fang (8). The equipment and procedure coincide with AASHO designation T89-60 except that the procedure is performed just once. The criterion for this one-point test is that the number of blows required to close the groove should lie between 17 and 36. Fang defined the relationship between the moisture content at any given number of blows and the moisture content at the liquid limit (i.e. 25 blows) as follows:

$$LL = W_N + I_f \log \frac{N}{25}$$

where:

LL = Liquid limit

W_N = Sample moisture content at N blows (between 17 and 36)

N = Number of blows

I_f = Flow index

The flow index is defined in terms of the one-point moisture content as follows:

$$I_f = 0.36\, W_N - 3$$

Figures 1 and 2 present the foregoing relationships in graphical form.

The determination of the liquid limit consists of using the one-point moisture content to determine a flow index. The flow index, the number of blows, and the one-point moisture content are then used in conjunction with Figure 2 to obtain the value for the liquid limit.

The use of Figures 1 and 2 was applied to available data on 334 soil samples from the JHRP laboratory at Purdue. All data obtained, using between 17 and 36 blows, were used as though they had been the only point obtained. The liquid limit thus obtained was compared to the liquid limit obtained by the standard flow curve procedure.

The differences between standard liquid limit and one-point liquid limit were studied to determine if significant differences existed between these methods.

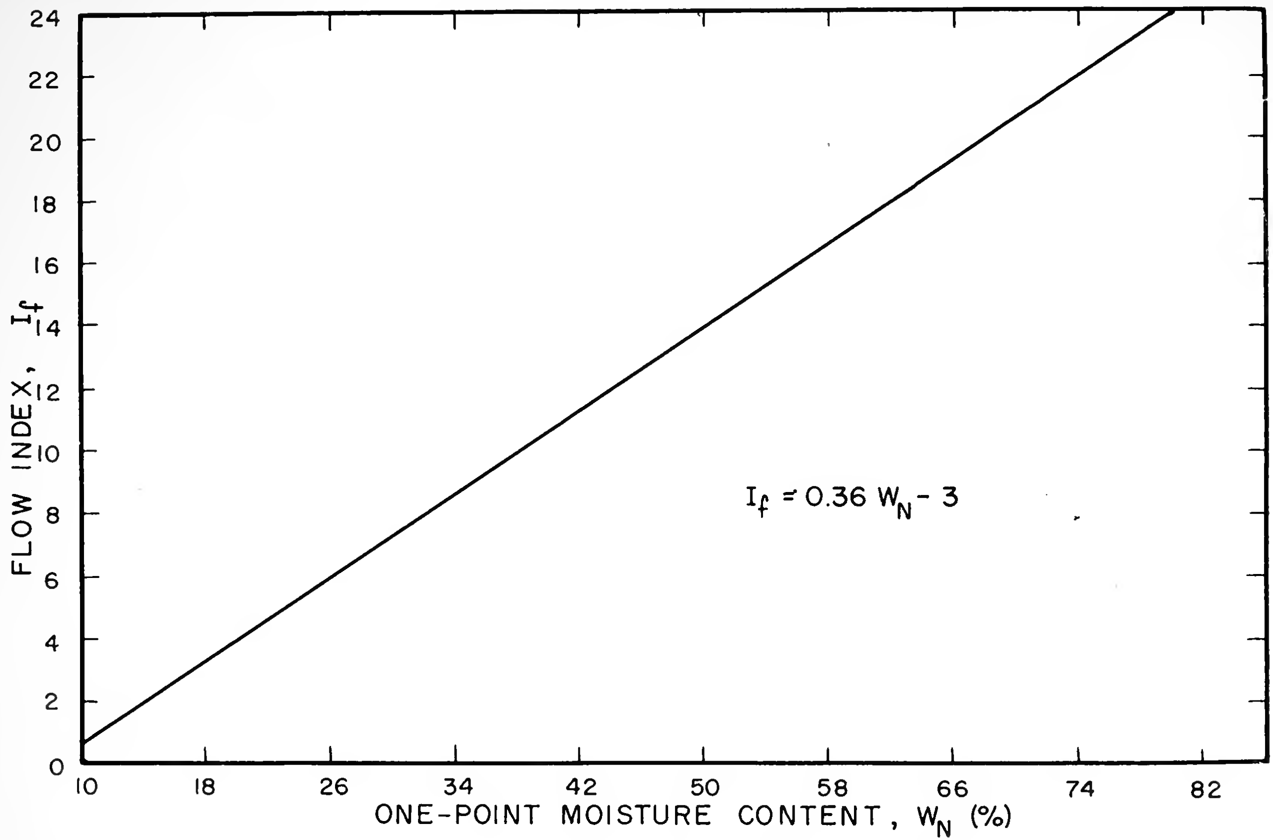


FIG. 1 FLOW INDEX FOR ONE-POINT LIQUID LIMIT (FANG)

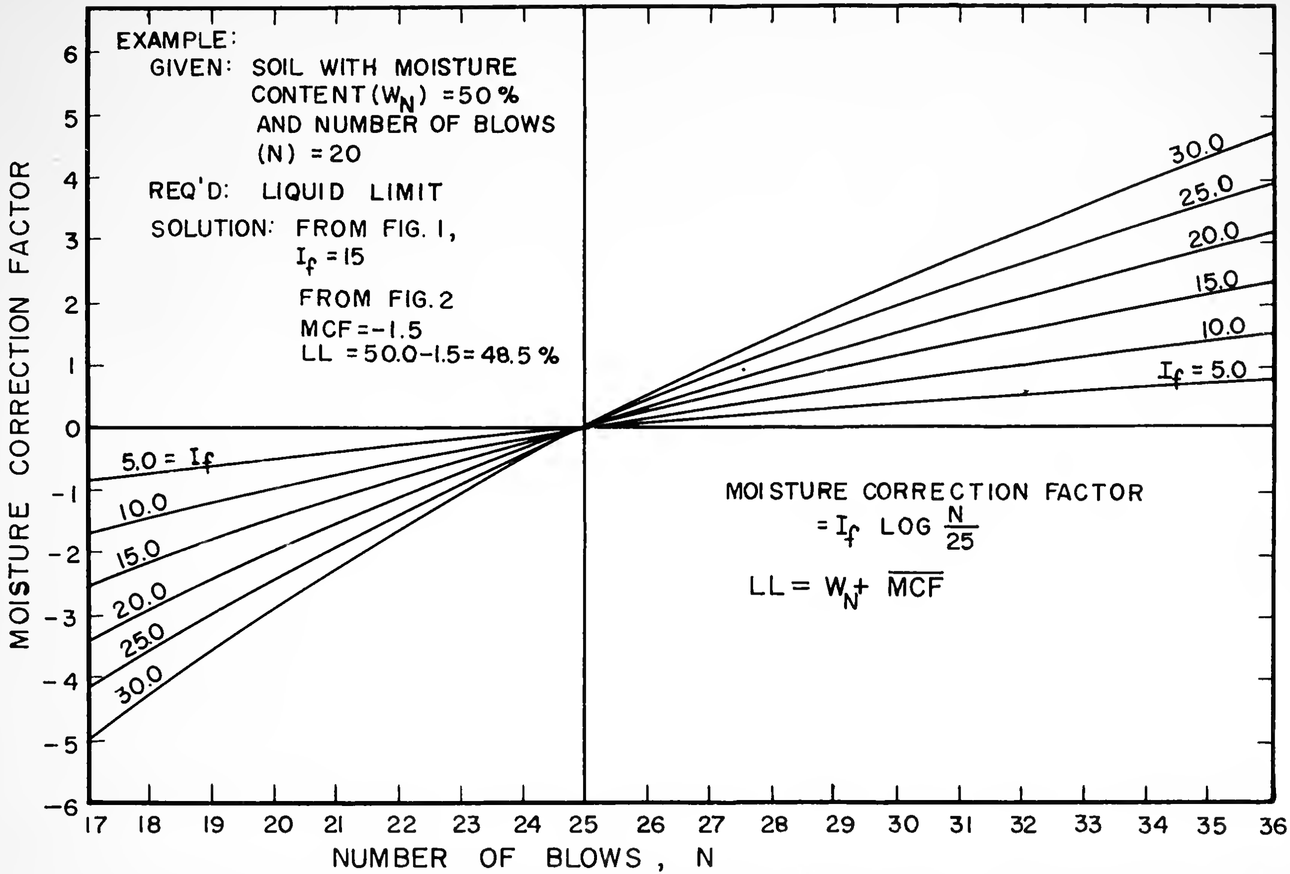


FIG. 2 MOISTURE CORRECTION FACTORS FOR ONE-POINT LIQUID LIMIT (FANG)

The "squash" test was used as an alternative method for the determination of the plastic limit. This method consists of forming a ball of the moist soil about one half inch in diameter. This ball is then squashed between two glass plates to form a soil pat. As the soil dries, this squashing will cause cracks to develop on the surface of the soil pat. The moisture content at which these cracks developed across the entire surface was taken as the plastic limit of that soil.

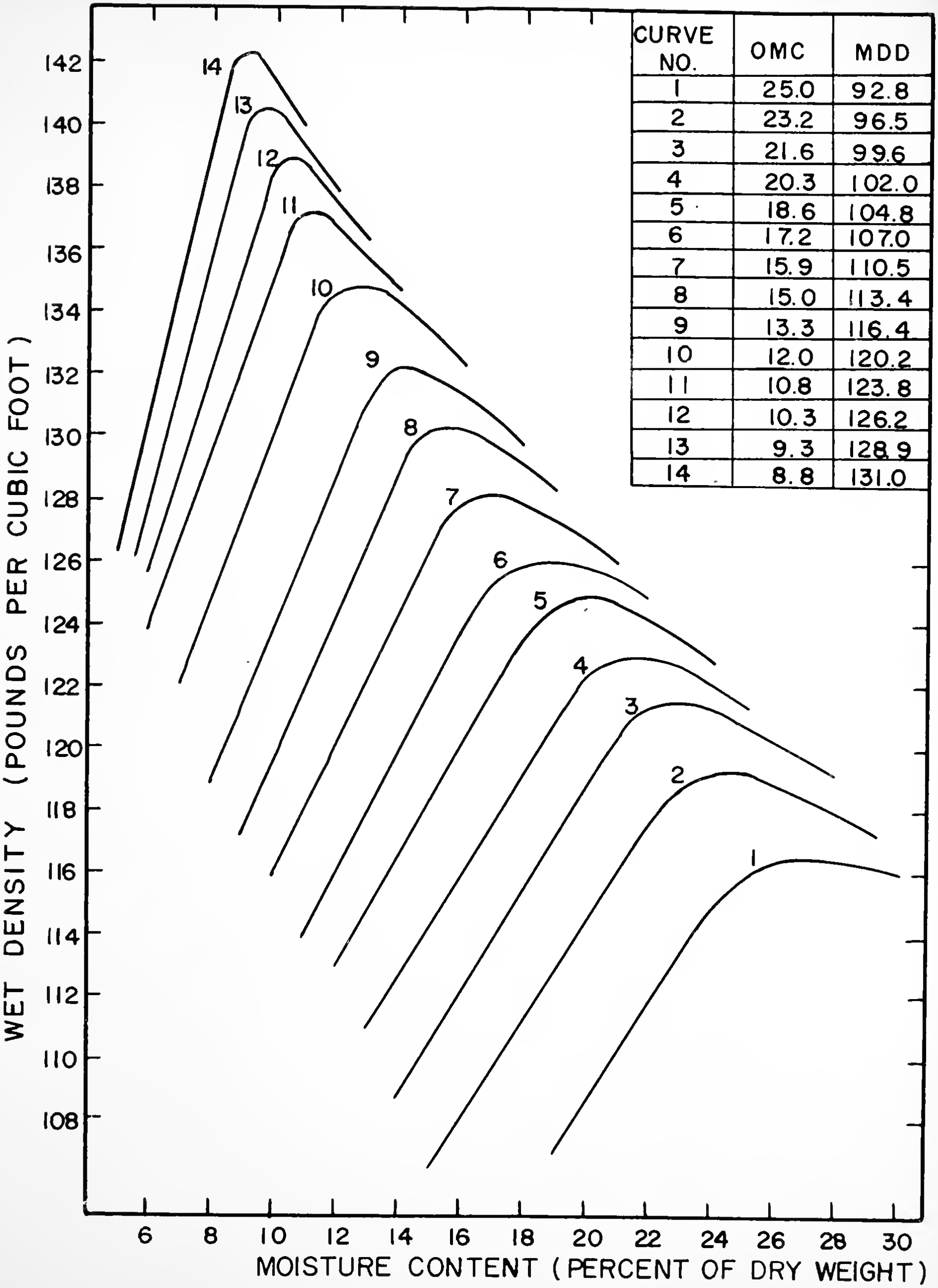
Both the standard thread method and the squash method were applied to 32 soil samples. The difference between results was noted and the 32 differences thus obtained were studied to determine if significant difference existed between the methods.

Moisture-Density Relationship of Soil

The standard procedure for determining the moisture-density relationship of soil is outlined in AASHO designation T99-57.

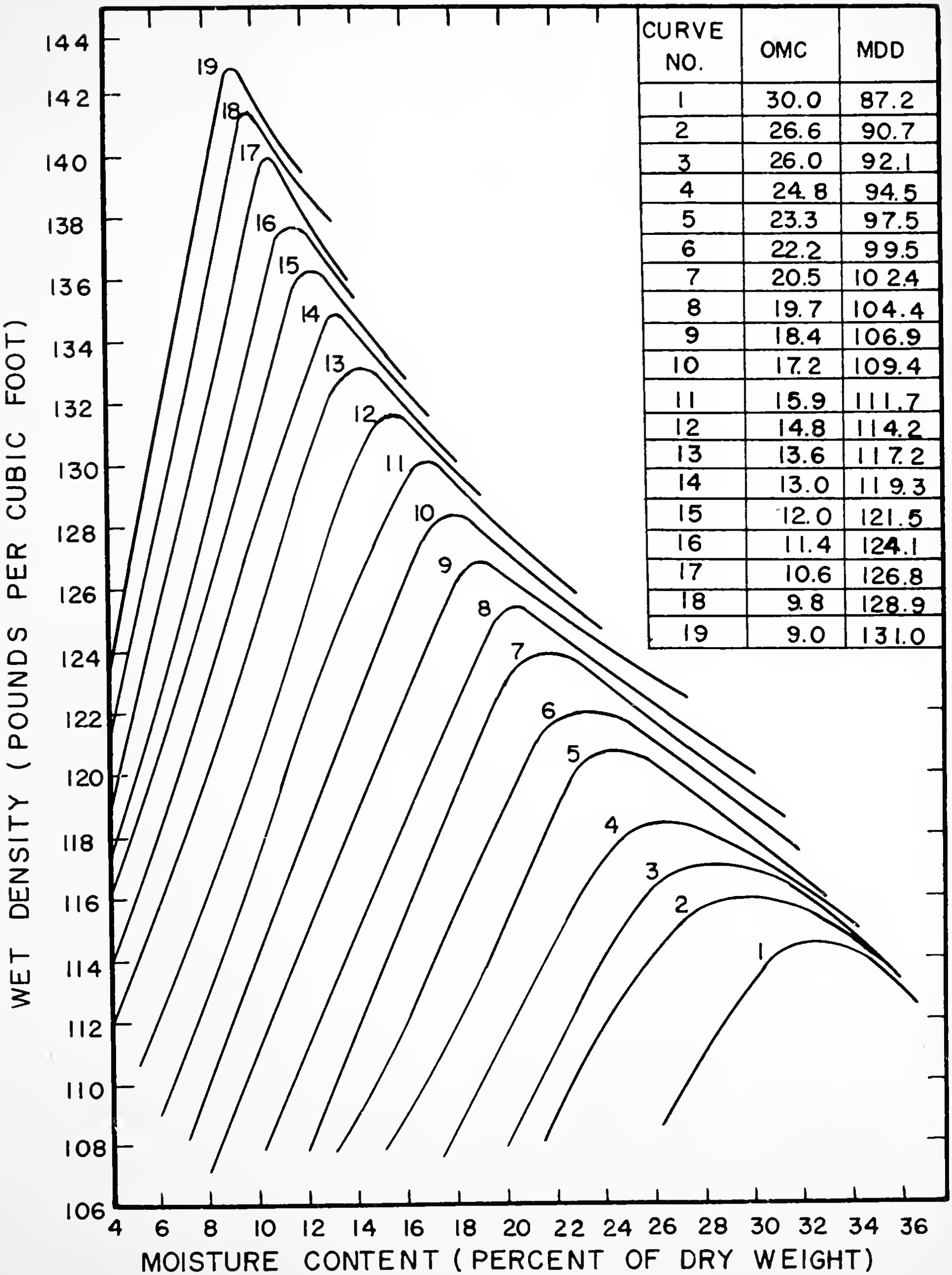
The abbreviated procedure studied utilized the typical moisture-density curves developed by the Indiana State Highway Department (16) and the Ohio State Highway Department (23). These sets of typical curves are shown in Figure 3 and Figure 4 respectively.

The procedure adheres to the standard procedure except the steps are performed just once. The moisture content and wet density thus obtained are plotted on the set of typical curves to establish the typical curve to be utilized.



CURVE NO.	OMC	MDD
1	25.0	92.8
2	23.2	96.5
3	21.6	99.6
4	20.3	102.0
5	18.6	104.8
6	17.2	107.0
7	15.9	110.5
8	15.0	113.4
9	13.3	116.4
10	12.0	120.2
11	10.8	123.8
12	10.3	126.2
13	9.3	128.9
14	8.8	131.0

FIG. 3 INDIANA TYPICAL MOISTURE-DENSITY CURVES (SPENCER)



CURVE NO.	OMC	MDD
1	30.0	87.2
2	26.6	90.7
3	26.0	92.1
4	24.8	94.5
5	23.3	97.5
6	22.2	99.5
7	20.5	102.4
8	19.7	104.4
9	18.4	106.9
10	17.2	109.4
11	15.9	111.7
12	14.8	114.2
13	13.6	117.2
14	13.0	119.3
15	12.0	121.5
16	11.4	124.1
17	10.6	126.8
18	9.8	128.9
19	9.0	131.0

FIG. 4 OHIO TYPICAL MOISTURE-DENSITY CURVES (WOODS AND LITEHISER)

The optimum moisture content, OMC, and maximum dry density, MDD, are then determined from the small table in each graph. Interpolation between curves is sometimes necessary.

Available data of the JHRP laboratory were utilized in a comparison of the standard and one-point compaction methods. Three hundred and twelve compaction tests were studied to achieve this comparison. All moisture contents lying within a range of 5 percentage points below OMC and 4 percentage points over OMC were used with their corresponding wet density as though they were the only information available. These data are hereinafter referred to as "one-point" OMC and MDD. Both the Ohio typical curves and the Indiana typical curves were used in this study.

In addition, a multiple regression analysis was made using the OMC and MDD and classification properties. This technique yielded formulas for the prediction of OMC and MDD as functions of the classification properties. A purely linear model was utilized in the following form:

$$Y = b_o + b_1X_1 + b_2X_2 + \ldots + b_kX_k$$

where:

Y = Predicted dependent variable, OMC or MDD

X_i = Independent classification properties, $i = 1, 2, 3, \ldots, k$

b_i = Constants, $i = 1, 2, 3, \ldots, k$

The independent variables were chosen on the basis of availability and results of previous studies. The variables chosen were:

1. Plastic Limit, PL
2. Liquid Limit, LL
3. Plasticity Index, PI
4. Percent coarse material, G. Defined as the percent retained on a No. 40 sieve.
5. Percent fine sand, S. Defined as the percent passing the No. 40 sieve but larger than 0.05 mm.
6. Percent fines, F. Defined as the percent finer than 0.05 mm.
7. Group Index, GI. Defined according to AASHO soil classification system.
8. Fineness Average, FA. Determined by taking one-sixth of the total percentages, by weight, finer than the following sizes: No. 10 sieve, No. 40 sieve, No. 200 sieve, 0.02 mm, 0.005 mm, and 0.001 mm.

A separate regression analysis was performed on A-horizon soils, B-horizon soils, C-horizon soils, and nonplastic soils.

The multiple regression analysis was performed on a computer in a stepwise procedure which added the independent variables to the predicting equation in the order of their contribution to the prediction. Thus, the best prediction equation did not necessarily include all variables. This technique developed the prediction formulas and gave an estimate of the error to be expected in their use. This error was compared to the error associated with the standard test to evaluate the reliability of the prediction equations.

California Bearing Ratio

For purposes of this study the standard procedure for the determination of the California Bearing Ratio conformed to that defined by the U. S. Army Corps of Engineers in EM 1110-45-302, Appendix III, 1957, part 5. The standard AASHO compactive effort was used throughout the testing program. The molding moisture content was at all times within $\pm$ 0.5 percentage points of the optimum moisture content determined by the standard AASHO compaction test.

To determine the variability of test results associated with the above procedure, a series of CBR tests was made on each of three soil types. The three soil types chosen for study included:

1. a low plasticity silty clay
2. a highly plastic clay
3. a nonplastic granular material

The results of these tests were analyzed to determine the "error of measurement" associated with the CBR test itself. It was assumed that variability not attributable to measurement error was due to variations in soil type.

To explain the variability due to soil type, the classification properties were used in conjunction with a multiple regression analysis to obtain predicting formulas for the CBR in terms of the classification properties. The procedure for the performance of this regression analysis was identical to that described for the moisture-density test. For the CBR study the molded moisture content and molded dry

density were added to the list of independent variables. The data were separated by horizon and a stepwise regression was performed by a computer.

RESULTS AND ANALYSIS OF RESULTS

Atterberg Limits

The utilization of all data obtained with between 17 and 36 blows from 334 standard liquid limit tests provided the basis for comparing results of the one-point method with those of the standard method. Each one-point determination was paired with the standard method result and the difference between them was obtained. In this manner 968 differences were obtained.

Figure 5 summarizes this information by showing the frequency with which a given difference occurred. The differences form a unimodal distribution with a mean of 0.17 percentage points and a standard deviation of 1.0 percentage points. The standard deviation is a measure of the diversity of the data about their mean and is defined by the formula:

$$S = \sqrt{\frac{\sum_{i=1}^{N} (D_i - \overline{D})^2}{N - 1}}$$

where

S^2 = An unbiased estimate of the standard deviation squared.

D_i = Difference between any particular one-point liquid limit and the corresponding standard liquid limit.

$\overline{D}$ = Mean difference between one-point liquid limit and standard liquid limit.

N = Number of determinations.

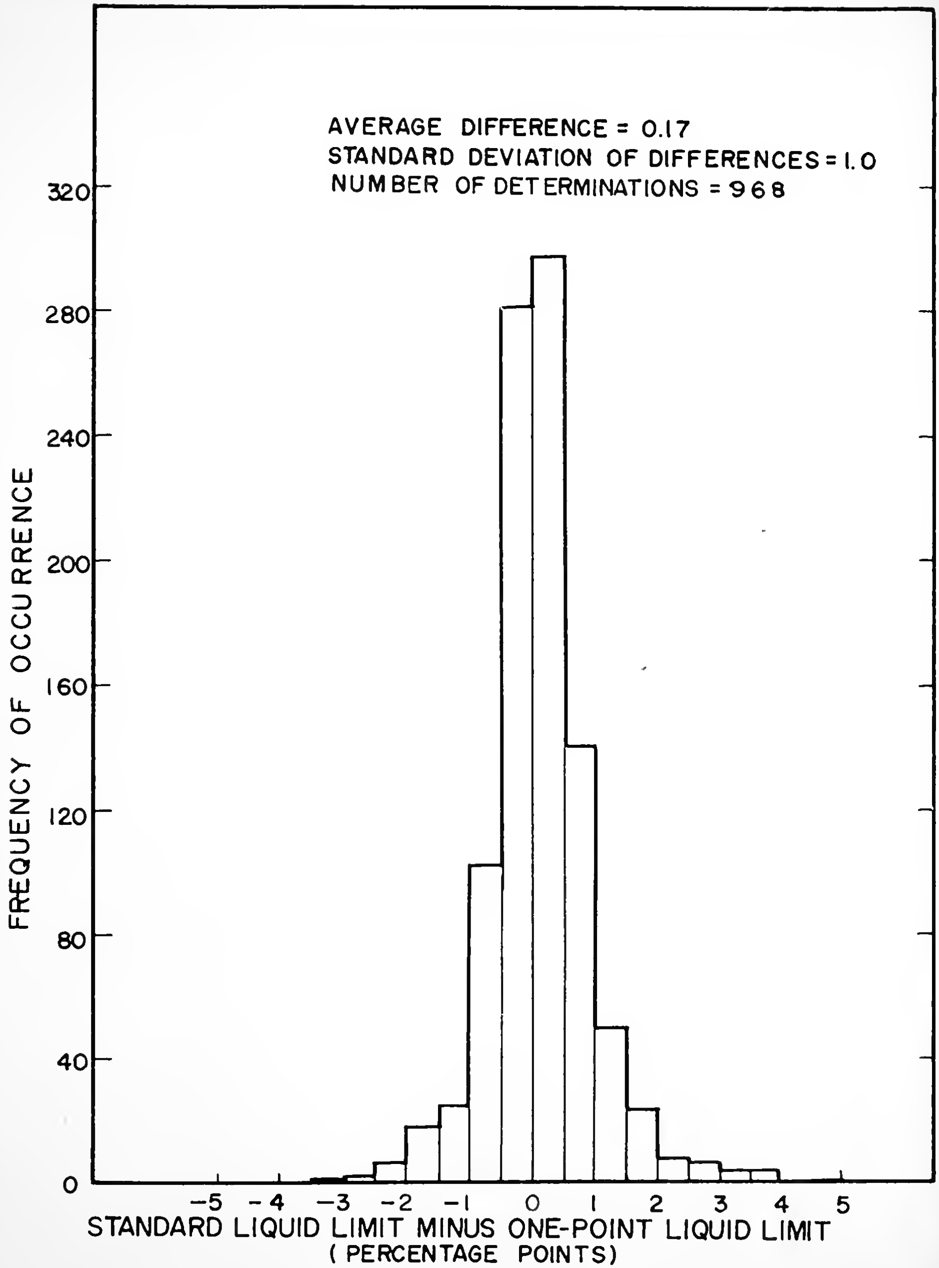


FIG. 5 FREQUENCY POLYGON FOR DIFFERENCES BETWEEN STANDARD AASHO LIQUID LIMIT AND ONE-POINT LIQUID LIMIT

Figure 6 shows the percent of the differences between one-point liquid limit and standard liquid limit which lie within a given absolute difference from zero. It can be seen that 85 percent of the observed differences lie with $\pm$ 1.0 percentage point and 97 percent within $\pm$ 2.0 percentage points.

The plastic limit study consisted of a comparison of the standard thread method and the squash method previously defined. Both methods were applied to 32 soil samples. The results obtained from each method were paired and a series of differences were obtained. The frequency with which given differences occurred is shown in the frequency polygon of Figure 7.

The small number of samples studied necessitated the formulation of an adequate comparison. Ostle (12) outlines a procedure for comparison of paired observations. The method consists of a quantitative evaluation of the hypothesis that the mean difference between paired observations is zero. The test statistic, t, is comparied to the theoretical Student"s t distribution. If the test statistic is larger than the theoretical value, the hypothesis of insignificant difference is rejected. Utilizing the mean and the standard deviation of the differences as shown on Figure 7, this quantitative comparison was performed as follows.

Hypothesis: $\bar{D}' = 0$

Alternate Hypothesis: $\bar{D}' \neq 0$

Test Statistic: $t = \dfrac{\bar{D} - \bar{D}'}{\sqrt{S^2/N}}$

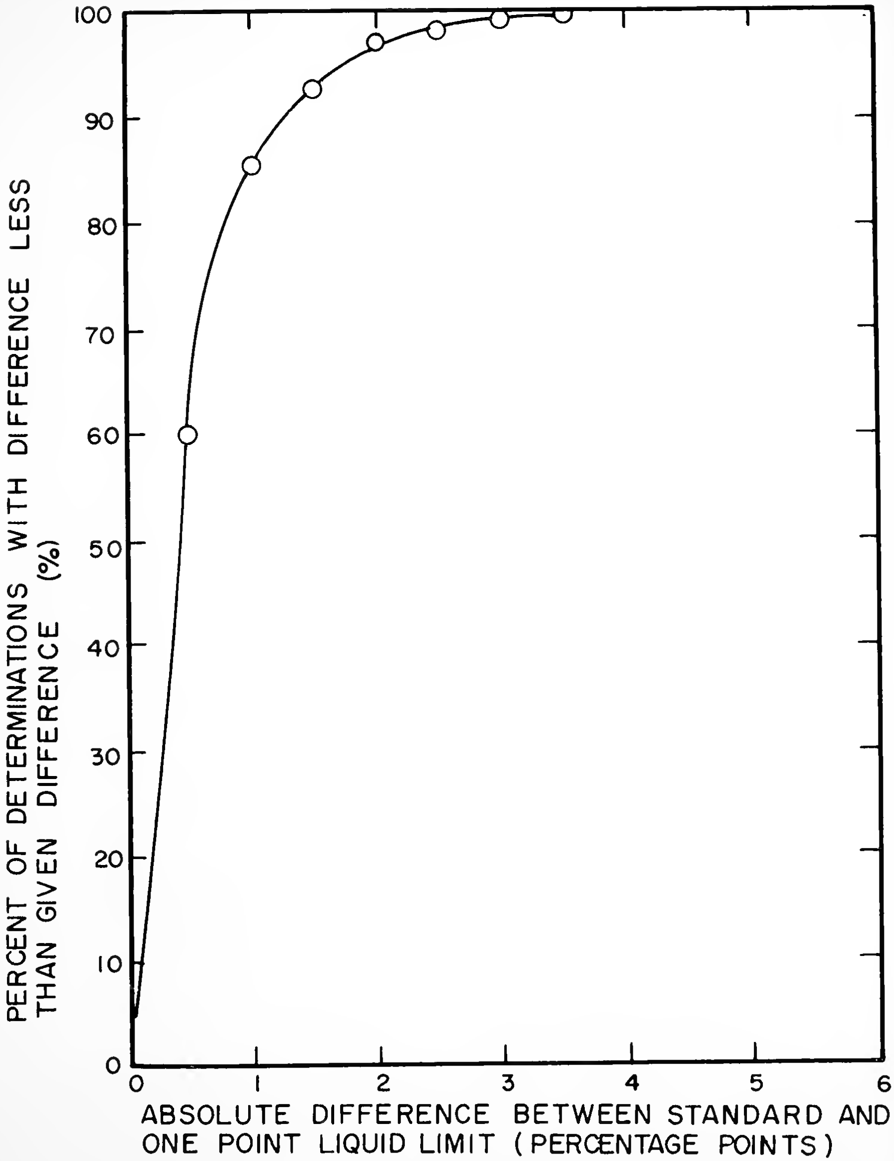


FIG. 6 PERCENT OF TOTAL DETERMINATIONS OF ONE-POINT LIQUID LIMIT DISPLAYING LESS THAN GIVEN ABSOLUTE DIFFERENCE FROM STANDARD LIQUID LIMIT

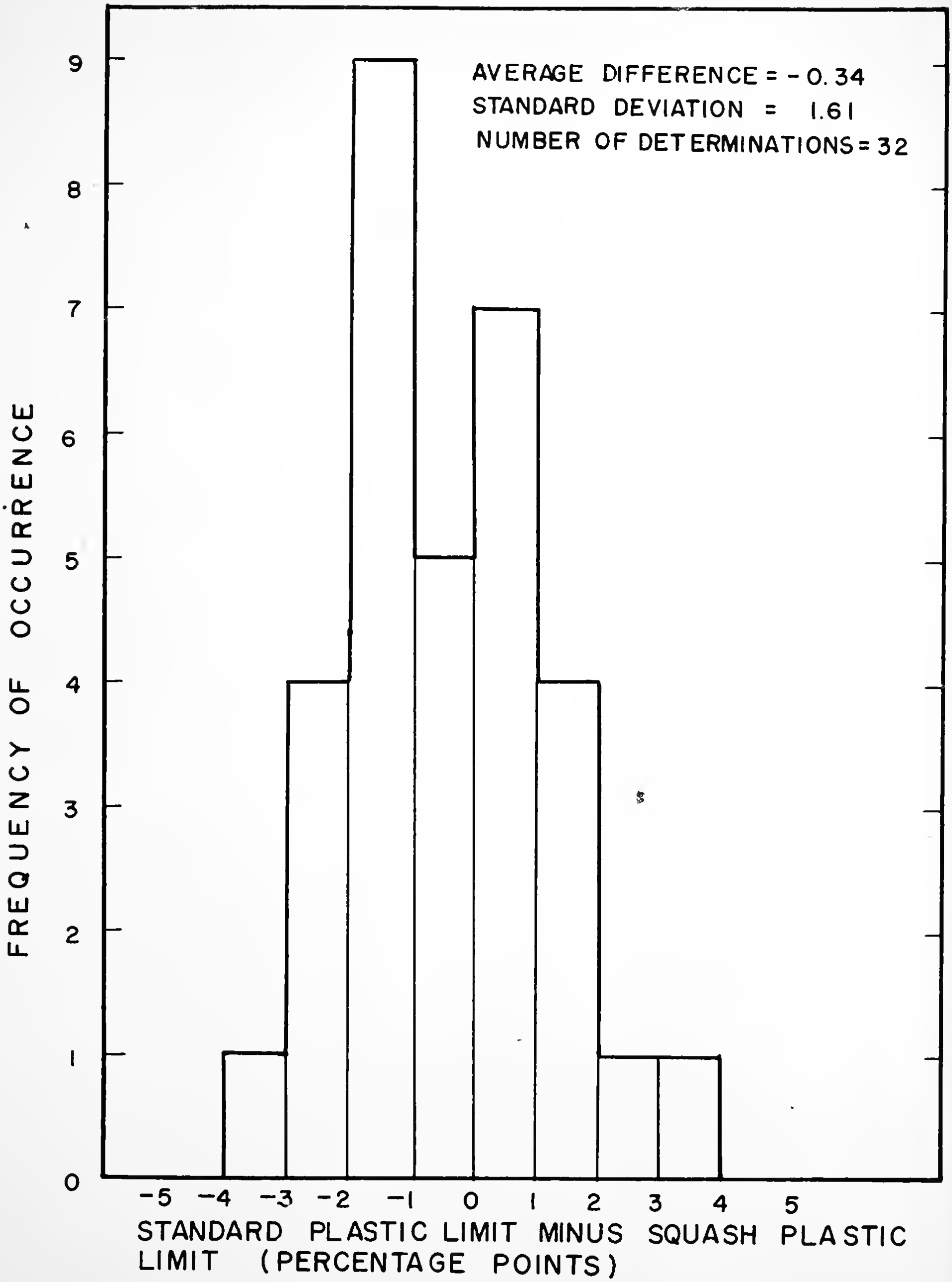


FIG. 7 FREQUENCY POLYGON FOR DIFFERENCES BETWEEN STANDARD AASHO PLASTIC LIMIT AND SQUASH PLASTIC LIMIT

where:

$\bar{D}'$ = Hypothesized average difference between squash plastic limit and standard plastic limit.

$\bar{D}$ = Average difference for sample studied.

N = Number of paired observations.

S = Unbiased estimate of the standard deviation.

The theoretical Student's t for N-1 degrees of freedom and a level of significance of 0.05 is equal to 2.04. The level of significance, or the α-level, is the probability of rejecting a hypothesis which is in reality true. It is desirable that this value be small and 0.05 is the value commonly used in research.

$$t = \frac{-\ 0.34 - 0}{\sqrt{\frac{2.59}{32}}} = -1.20$$

$$t^{0.05}_{31\ d.f.} = 2.04 > 1.20$$

Therefore the hypothesis was accepted and the difference between the standard method results and the squash method results for the determination of the plastic limit was considered insignificant.

Moisture-Density Relationship of Soils

Figure 8 depicts the frequency with which differences occurred in the optimum moisture content obtained by the one-point method from that obtained by the standard method. The arithmetic mean of the differences was found to be -0.84

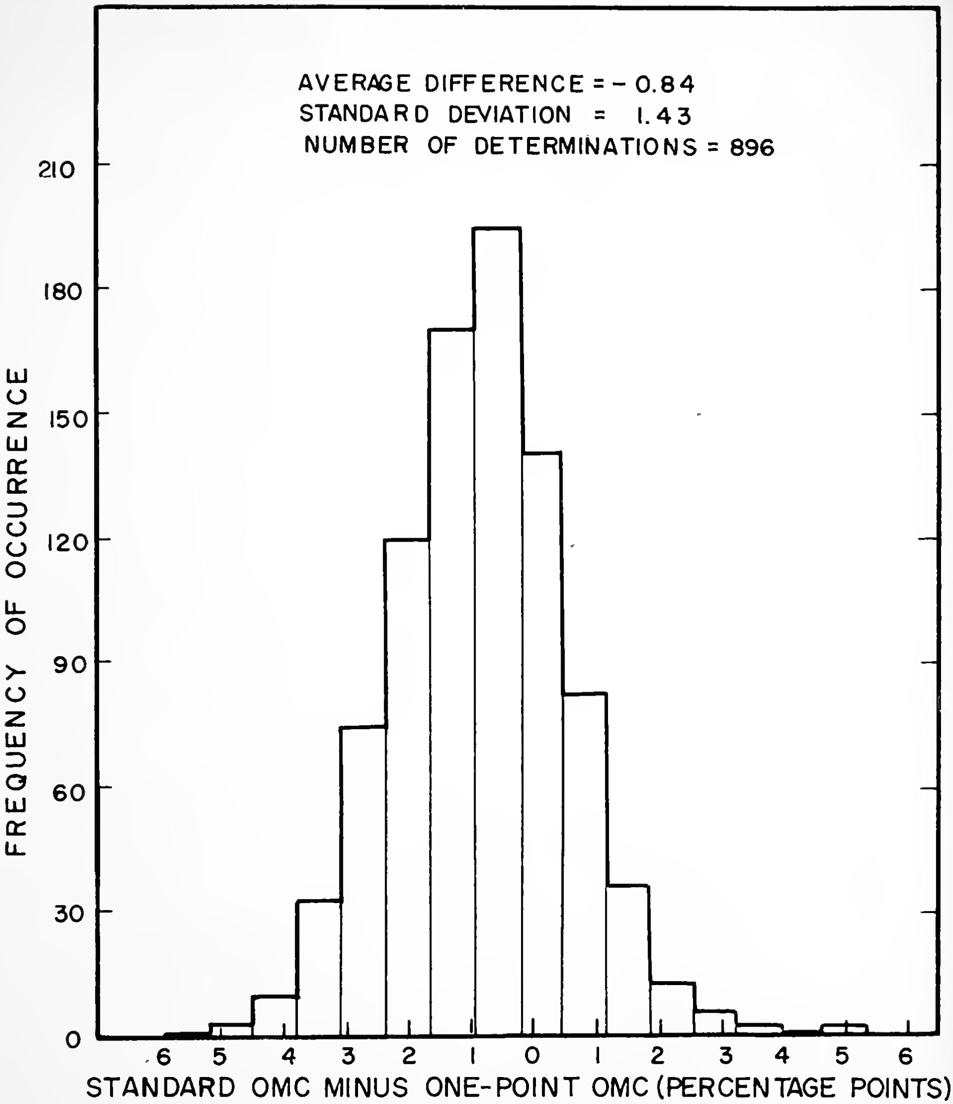


FIG. 8 FREQUENCY POLYGON FOR DIFFERENCES BETWEEN STANDARD AASHO OPTIMUM MOISTURE CONTENT AND ONE-POINT OPTIMUM MOISTURE CONTENT FROM OHIO TYPICAL CURVES

percentage points indicating that "on the average" the optimum moisture content obtained from the Ohio typical curves is 0.84 percentage points higher than that obtained by the standard method. The standard deviation of the differences was found to be 1.43 percentage points.

Figure 9 shows the frequency distribution of the differences between standard maximum dry density and one-point maximum dry density obtained from the Ohio typical curves. The mean difference was determined to be 0.30 pcf indicating that the Ohio typical curves yield a maximum dry density which is, on the average, 0.30 pcf less than the value obtained by the standard method. The standard deviation of the distribution is 1.94 pcf.

The frequency distribution of the differences between the standard method optimum moisture content and the one-point value obtained from the Indiana typical curves is shown in Figure 10. The arithmetic mean between the results of these methods was determined to be -0.19 percentage points indicating that on the average the optimum moisture content obtained from the Indiana typical curves is 0.19 percentage points higher than that obtained by the standard method. The standard deviation of this distribution is 1.45 percentage points.

Figure 11 presents a frequency distribution for the differences between the standard method maximum dry density and the one-point value obtained from the Indiana typical curves. The mean difference is shown to be 0.20 pcf indicating that

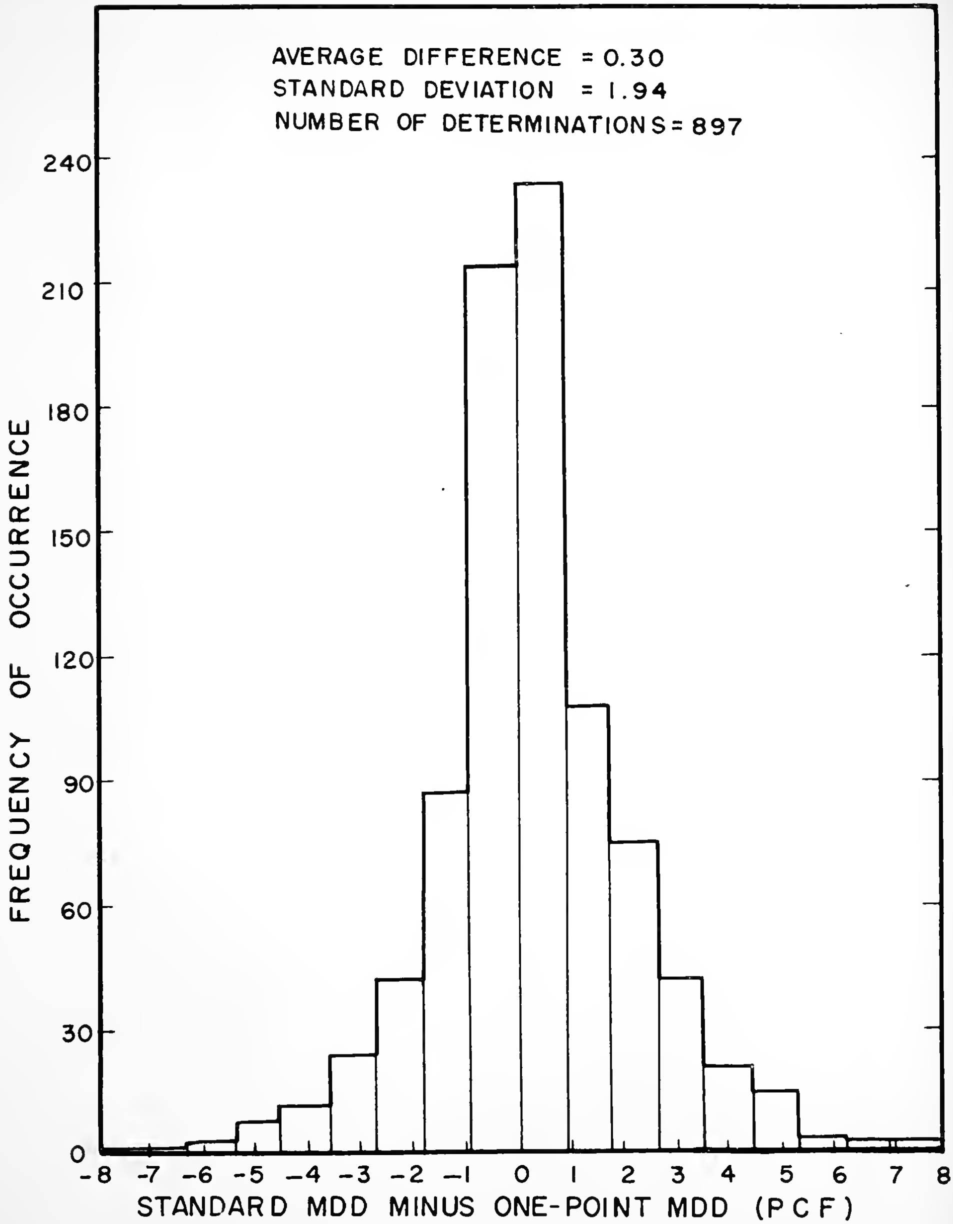


FIG. 9 FREQUENCY POLYGON FOR DIFFERENCE BETWEEN STANDARD AASHO MAXIMUM DRY DENSITY AND ONE-POINT MAXIMUM DRY DENSITY FROM OHIO TYPICAL CURVES

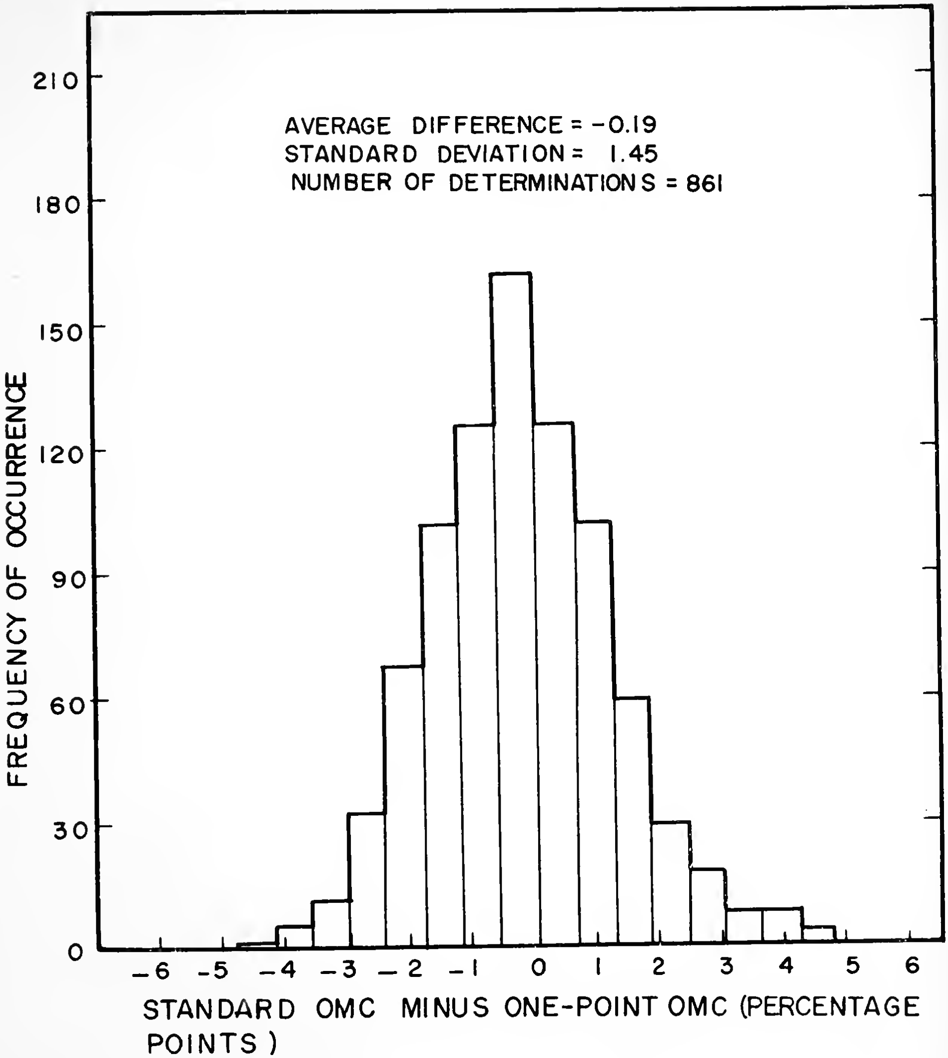


FIG. 10 FREQUENCY POLYGON FOR DIFFERENCES BETWEEN STANDARD AASHO OPTIMUM MOISTURE CONTENT AND ONE-POINT OPTIMUM MOISTURE CONTENT FROM INDIANA TYPICAL CURVES

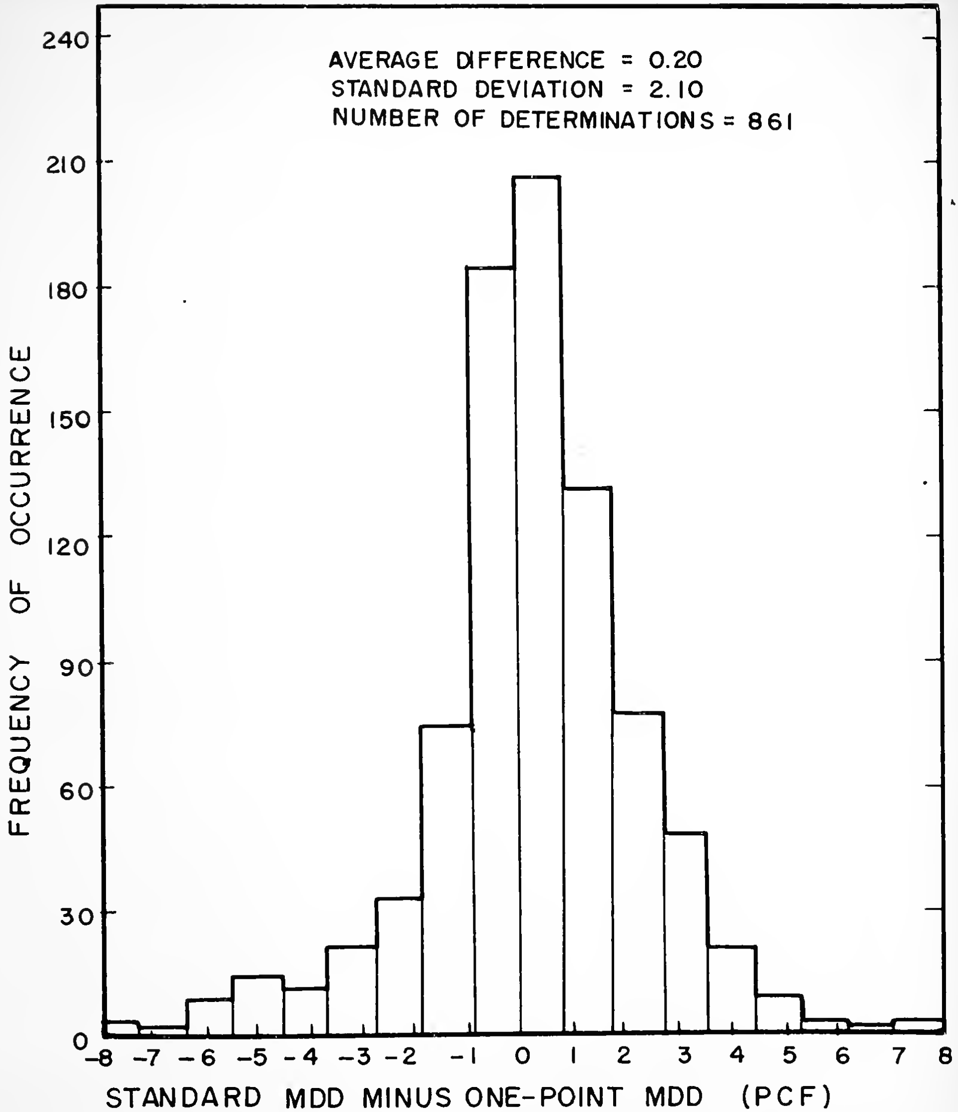


FIG. 11 FREQUENCY POLYGON FOR DIFFERENCES BETWEEN STANDARD AASHO MAXIMUM DRY DENSITY AND ONE-POINT MAXIMUM DRY DENSITY FROM INDIANA TYPICAL CURVES

on the average the maximum dry density obtained from the Indiana typical curves is 0.20 pcf less than that obtained by the standard method. The standard deviation of the differences is shown to be 2.10 pcf.

Note that the four foregoing figures depict a unimodal distribution approximating the normal distribution. Figure 12 shows the relationship between percent of total determinations and absolute difference from zero.

It is seen that with the Indiana typical curves the one-point optimum moisture content lies within 3.0 percentage points of the standard optimum moisture content 95 percent of the time. With the Ohio typical curves the optimum moisture content lies within 3.4 percentage points 95 percent of the time. The one-point maximum dry density values lie within 5 pcf of the standard method values approximately 95 percent of the time for both the Indiana and the Ohio typical curves.

Table 1 summarizes the statistics for the one-point moisture-density test evaluation.

Equations for the prediction of the optimum moisture content and maximum dry density are given in Appendix A. The results are placed into four groups according to soil type. Within each group are:

1. Formulas for predicting the maximum dry density using the classification properties
2. Formulas for predicting the optimum moisture content using the classification properties

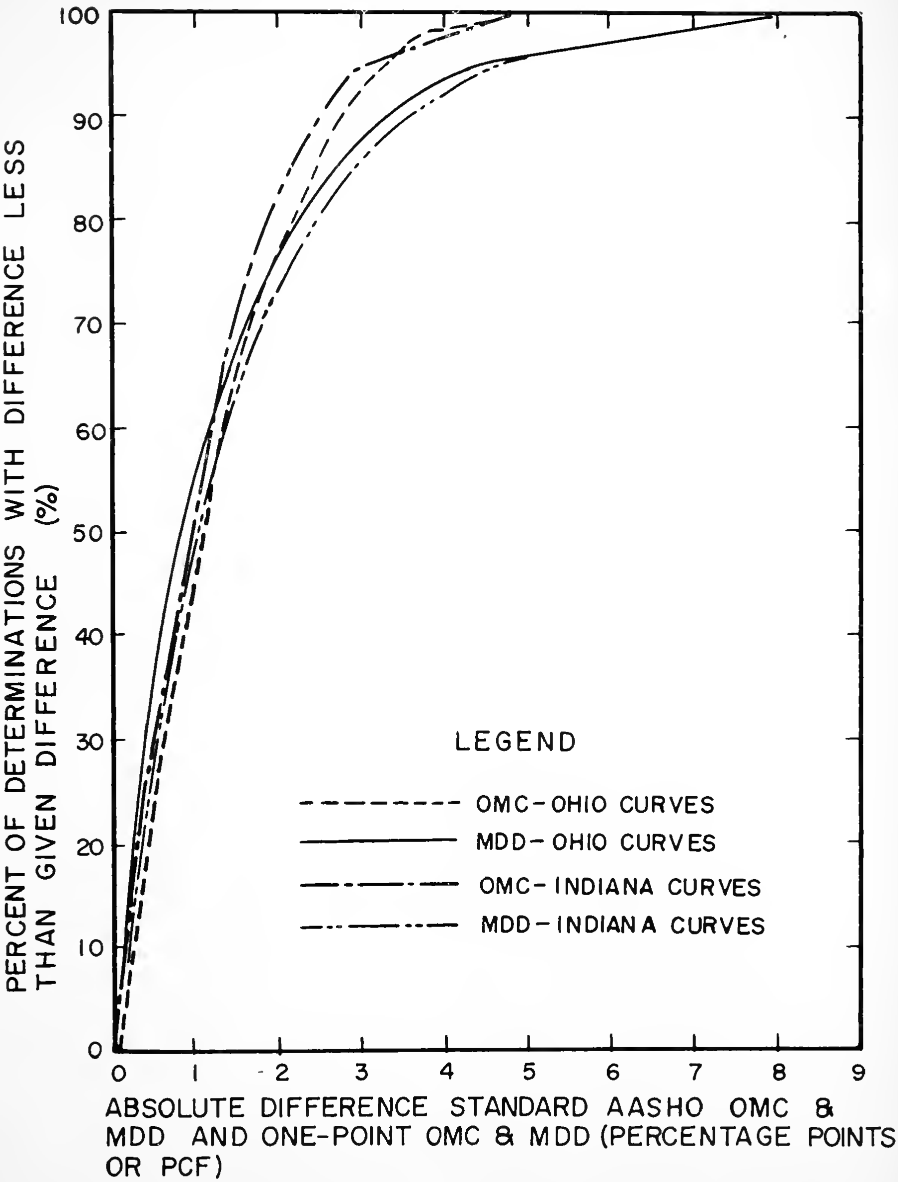


FIG. 12 PERCENT OF TOTAL DETERMINATIONS OF ONE-POINT COMPACTION VALUES DISPLAYING LESS THAN GIVEN ABSOLUTE DIFFERENCE FROM STANDARD COMPACTION VALUES

TABLE 1. SUMMARY OF ONE-POINT COMPACTION EVALUATION

Typical Curves	Difference	Mean Difference $\bar{D}$	Standard Deviation
Ohio	Standard OMC minus one point OMC	-0.84 percentage points	1.43 percentage points
	Standard MDD minus one point MDD	0.30 pcf	1.94 pcf
Indiana	Standard OMC minus one point OMC	-0.19 percentage points	1.45 percentage points
	Standard MDD minus one point MDD	0.20 pcf	2.10 pcf

3. Formulas for predicting the maximum dry density using the classification properties and the optimum moisture content.

The exception to this format is the nonplastic soil group which gives the maximum dry density as a function of the classification properties and the optimum moisture content as a function of the maximum dry density. All formulas are linear and of the form:

$$Y = b_0 + b_1x_1 + b_2x_2 + \ldots + b_kx_k$$

The regression analysis was performed by computer in a stepwise manner whereby the independent variables were added to the formula in the order that they contributed to the prediction. An estimate of the reliability associated with these formulas is given by the standard error.

As variables are added to the formulas in Appendix A, the standard error decreases, or the formula reliability increases. A point is reached, however, beyond which further addition of variables does not improve the reliability. Addition of variables beyond this point, while not improving the reliability, may increase the R^2 value. R^2 is a squared multiple correlation coefficient and represents the fraction of the variability in the dependent variable which is explained by the regression formula. The highest R^2 is seen to appear with the formulas including the largest number of variables. A reduced rate of increase in R^2 usually accompanied the point at which the standard error became constant. Thus, to minimize the number of variables and to maximize the prediction

reliability, the formula chosen was that corresponding to the point in the stepwise regression at which the standard error became constant or was a minimum.

In this manner, prediction equations for A-, B- and C-horizon soils and for nonplastic soils were chosen. These are shown in Table 2.

California Bearing Ratio

To determine the error of measurement of the California Bearing Ratio a series of CBR determinations was performed on each of three soil types. The results of these determinations were studied in a one-way classification analysis of variance. Table 3 summarizes the properties of soils studied. Soil No. 1 is a silty clay, No. 2 is a high plasticity clay, typical of those encountered in B-horizon soils, and No. 3 is a well graded, nonplastic, granular material. Several CBR tests were performed on each of these soils according to procedures previously outlined. Table 4 summarizes the results of these CBR determinations.

The one-way classification analysis of variance provides an estimate of the error of measurement by separating the total variability into measurement error and variability due to soil type differences. Table 5 presents the analysis of variance table showing the estimate of variability which is attributable to soil type and that which is attributable to measurement error.

TABLE 2. SUMMARY OF BEST PREDICTION FORMULAS FOR OPTIMUM MOISTURE CONTENT AND MAXIMUM DRY DENSITY

Soil Type	Prediction Formula	Std. Error	R^2
A-Horizon	*$\overline{OMC} = 7.56 + 0.16LL - 0.19G + 0.27PL$	1.6	0.665
	$\overline{MDD} = 136.95 - 1.42\overline{OMC} - 0.32PL$	1.9	0.877
B-Horizon	$\overline{OMC} = 13.03 + 0.14GI - 0.06S + 0.10LL$	1.5	0.744
	$\overline{MDD} = 135.32 - 1.39\overline{OMC} - 0.12LL + 0.07S$	1.5	0.937
C-Horizon	$\overline{OMC} = 2.05 + 0.19LL + 0.30PL + 0.20GI$	1.5	0.814
	$\overline{MDD} = 144.07 - 1.64\overline{OMC} - 0.05F - 0.13PI + 0.05G$	1.7	0.949
Nonplastic	$\overline{MDD} = 128.63 - 0.22S$	4.3	0.577
	$\overline{OMC} = 32.8 - 0.18\overline{MDD}$	1.3	0.463

*All symbols used in Table 2 are as defined in Appendix A.

TABLE 3. PROPERTIES OF SOILS USED IN DETERMINATION OF ERROR OF CBR MEASUREMENT

Soil No.	1	2	3
Liquid Limit (%)	33	53	NP
Plastic Limit (%)	22	23	NP
Plasticity Index (%)	11	30	—
Maximum Size	0.84mm (No. 20 Sieve)	0.42mm (No. 40 Sieve)	3/4"
Passing No. 4 Sieve (%)	100	100	58
Passing No. 200 Sieve (%)	93	96	10
Finer than 0.002 mm (%)	26	40	3
Maximum Dry Density (pcf)	108.9	100.4	141.6
Optimum Moisture Content (%)	16.6	21.3	6.4
AASHO Class	A-6(8)	A-7(19)	A-1(0)
Unified Class	CL	CH	SW-SM

TABLE 4. SUMMARY OF CBR TEST RESULTS

Soil No.	Molded Dry Density (pcf)	Molded Moisture Content (%)	0.1" CBR(%)
1	108.2	16.8	15
	108.3	16.9	11
	107.0	16.6	15
	107.1	16.6	20
	107.9	16.6	22
2	101.8	21.2	9
	102.2	20.8	11
	101.1	21.5	8
	101.8	21.3	8
	101.2	21.6	8
3	140.8	6.0	90
	140.0	5.3	102
	138.8	6.2	94
	137.8	6.1	99

TABLE 5. ANALYSIS OF VARIANCE TABLE FOR CALIFORNIA BEARING RATIO

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square
Soil Type	20,096.6	2	10,048.3
Measurement Error	168.8	11	15.3
Total	20,265.4	13	——

The mean square associated with the measurement error is an indication of the variability in the CBR which is attributable to the testing procedure. Considering all soil types simultaneously, an estimate, S_e, of the standard error of measurement for the CBR test is equal to the square root of the mean square error.

$$S_e = \sqrt{15.3} = 3.91$$

The utilization of the foregoing analysis of variance technique required the assumption that the variability of the CBR was constant between soil groups. Examination of Table 4 reveals that this is not strictly true. Greater variability is seen to exist for soil No. 1 and 3 than for soil No. 2.

Consideration of the groups individually yields an estimate of the standard error of measurement associated with that soil group. This estimate is given by the following relationship.

$$S_e^i = \sqrt{\frac{\sum_{j=1}^{n} (X_{ij} - \overline{X}_i)^2}{n_i - 1}}$$

where:

S_e^1 = Estimate of standard error of measurement associated with ith soil

X_{ij} = jth CBR determination for the ith soil

$\overline{X}_i$ = Mean CBR for ith soil

n_i = Number of CBR determination on the ith soil type

Using the above relationship, the standard error of measurement for soil No. 1, S_e^1, was found to be 4.40. Similarly, for soils No. 2 and No. 3, S_e^2 and S_e^3 were found to be 1.30 and 5.32 respectively. As indicated earlier, this standard error of measurement is indicative of the amount of scatter about the mean value to be expected of a group of data. The larger the standard error, the more scatter to be expected and consequently, the less accurate the results.

In the analysis of variance technique it is assumed that all variability which is not attributable to testing error is due to differences in soil type. According to Table 5, if the above assumption is true, differences in soil type explain the larger portion of the CBR variability. The definition of soil type has been traditionally associated with the soil classification properties.

Appendix B presents formulas expressing the relationships between the classification properties and the CBR. These formulas were obtained by the utilization of the multiple regression analysis technique, performed in a stepwise manner by an electronic computer. The computer also provided the

standard error of estimate, and the squared multiple correlation coefficient associated with each formula.

Within each soil group five different regression problems were performed. These problems are described as follows:

1. Dependent and all independent variables used in linear form as obtained from laboratory data.
2. Dependent variable converted to common logarithm for use in regression; all independent variables used in linear form.
3. Dependent and all independent variables converted to common logarithm for use in regression.
4. Dependent variable used in linear form; some of the independent variables converted to logarithmic form.
5. Same as problem 4 except a different set of independent variables was converted to common logarithms.

Examination of the equations of Appendix B reveals that little reduction in the standard error of estimate was obtained by the various logarithm conversions. The use of logarithms was felt to complicate the use of the formulas to the extent that any small improvement in the standard error of estimate was discounted. On this basis the equations of problem No. 1 were chosen as the most suitable for practical use. Within problem No. 1 a formula was chosen which minimized the standard error of estimate and the number of variables used and gave a squared correlation coefficient in the upper range of values obtained.

The prediction formulas of Appendix B include the molded moisture content, w, and the molded dry density, γ_d. The regression analysis was performed on available data of the JHRP laboratory. All data were carefully examined and the only tests used were those for which the molded dry density and molded moisture content corresponded very closely to the optimum moisture content and maximum dry density. These optimum conditions are expressed as functions of the classification properties in Table 2. When these expressions for MDD and OMC were substituted into the formulas of Appendix B for γ_d and w, expressions for the CBR as functions of the classification properties were obtained. Table 6 presents the best prediction formulas for CBR as obtained by the above procedure.

The process of obtaining the regression equations for optimum moisture content, maximum dry density, and CBR necessitated the determination of the simple correlation coefficients among the sample properties. This correlation coefficient measures the degree of association between two variables. The value of the coeffient varies between + 1.0 and - 1.0 with + 1.0 indicating a "perfect" direct relationship and - 1.0 indicating a "perfect" inverse relationship.

Tables No. 7, No. 8, No. 9, and No. 10 present the simple correlation coefficients among the soil properties of A-horizon soils, B-horizon soils, C-horizon soils, and nonplastic soils respectively.

TABLE 6. SUMMARY OF BEST PREDICTION FORMULAS FOR CALIFORNIA BEARING RATIO

Soil Type	Prediction Formula	Std. Error	R^2
A-Horizon	*CBR = 14.10 -0.05PL -0.14LL +0.16G -0.05S	3.4	0.342
B-Horizon	CBR = 0.28FA -0.13PI +0.08G -0.09GI -0.29 -0.09F	2.6	0.636
C-Horizon	CBR = 19.85 +0.48PL -0.73PI -0.20G -0.11S -0.61GI -0.18FA	3.9	0.479
Nonplastic	CBR = 35.12 +0.07S -0.44FA	9.1	0.180

*All symbols used in Table 6 are as defined in Appendix B.

TABLE 7. SIMPLE CORRELATION COEFFICIENTS: A-HORIZON SOILS

MDD	OMC	PL	LL	PI	G	S	F	GI	FA	CBR	
1.00	-0.91	-0.77	-0.72	-0.43	+0.13	+0.15	-0.18	-0.45	-0.08	+0.24	MDD
	1.00	+0.71	+0.69	+0.44	-0.19	-0.15	+0.20	+0.43	+0.14	-0.41	OMC
		1.00	+0.72	+0.26	+0.08	-0.16	+0.13	+0.41	+0.03	-0.10	PL
			1.00	+0.85	+0.11	-0.12	+0.09	+0.74	+0.16	-0.22	LL
				1.00	+0.09	-0.05	+0.02	+0.73	+0.21	-0.24	PI
					1.00	+0.09	-0.38	-0.11	-0.44	+0.14	G
						1.00	-0.95	-0.54	-0.74	-0.23	S
							1.00	+0.54	+0.82	+0.17	F
								1.00	+0.56	-0.08	GI
									1.00	+0.13	FA
										1.00	CBR

TABLE 8. SIMPLE CORRELATION COEFFICIENTS: B-HORIZON SOILS

MDD	OMC	PL	LL	PI	G	S	F	GI	FA	CBR	
1.00	-0.98	-0.34	-0.64	-0.24	+0.32	+0.54	-0.16	-0.61	-0.32	-0.38	MDD
	1.00	+0.21	+0.54	+0.12	-0.25	-0.43	+0.02	+0.51	+0.22	+0.44	OMC
		1.00	+0.74	+0.60	-0.37	-0.69	+0.65	+0.65	+0.57	-0.23	PL
			1.00	+0.87	-0.41	-0.74	+0.58	+0.91	+0.64	-0.10	LL
				1.00	-0.35	-0.62	+0.65	+0.80	+0.64	-0.39	PI
					1.00	+0.42	-0.74	-0.64	-0.83	+0.08	G
						1.00	-0.80	-0.79	-0.72	+0.12	S
							1.00	+0.73	+0.91	-0.38	F
								1.00	+0.82	-0.09	GI
									1.00	-0.23	FA
										1.00	CBR

TABLE 9. SIMPLE CORRELATION COEFFICIENTS: C-HORIZON SOILS

MDD	OMC	PL	LL	PI	G	S	F	GI	FA	CBR	
1.00	-0.94	-0.80	-0.85	-0.69	+0.60	+0.59	-0.75	-0.82	-0.68	-0.01	MDD
	1.00	+0.83	+0.87	+0.70	-0.50	-0.56	+0.67	+0.79	+0.62	-0.14	OMC
		1.00	+0.81	+0.50	-0.46	-0.60	+0.68	+0.71	+0.58	+0.14	PL
			1.00	+0.91	-0.45	-0.54	+0.63	+0.83	+0.61	-0.07	LL
				1.00	-0.35	-0.37	+0.46	+0.72	+0.50	-0.20	PI
					1.00	+0.35	-0.80	-0.64	-0.84	-0.25	G
						1.00	-0.76	-0.64	-0.59	-0.19	S
							1.00	+0.80	+0.88	+0.24	F
								1.00	+0.79	-0.06	GI
									1.00	+0.11	FA
										1.00	CBR

TABLE 10. SIMPLE CORRELATION COEFFICIENTS: NONPLASTIC SOILS

MDD	OMC	G	S	F	FA	CBR	
1.00	-0.69	+0.54	-0.74	+0.46	-0.04	-0.19	MDD
	1.00	-0.18	+0.24	-0.14	+0.07	+0.11	OMC
		1.00	-0.82	-0.10	-0.70	+0.18	G
			1.00	-0.49	+0.19	+0.05	S
				1.00	+0.74	-0.36	F
					1.00	-0.37	FA
						1.00	CBR

DISCUSSION

Atterberg Limits

The comparison between the one-point and standard liquid limits showed the one point liquid limit to be within 2.0 percentage points of the standard liquid limit approximately 97 percent of the time. Hampton (10) showed the error of measurement of the liquid limit as determined by the standard method to be 2.39 percentage points. The one-point liquid limit is therefore seen to yield results which lie within the limits of testing reliability.

Consideration of the decreased cost of determining the Atterberg limits by the abbreviated method gives added desirability to its use. During the months of August 1962 through March 1963 the one-point method for determining the liquid limit was used on 104 soil samples. The standard method for the plastic limit determination was used. The cost of testing, exclusive of calculation and preparation time, was $169.64 or $1.63 per test.

During a comparable six-month period from December 1961 through July 1962, 130 samples were tested using the standard methods for both liquid limit and plastic limit determination. The cost of determining the Atterberg limits during this period was $395.84 for a unit cost of $3.04. The time saving

factor of the one-point method is seen to have decreased the unit cost by $1.41 per test.

On the basis of the observation that a large percentage of one-point liquid limit values lie very close to the standard liquid limit value, it is concluded that use of the one point method is justifiable.

The comparisons of the standard roll-out method and the squash method for the determination of the plastic limit support the conclusion that there is no significant difference between the values obtained by these methods. Both methods require a subjective evaluation by the operator concerning the precise point in the procedure at which the plastic limit has been reached. The time required for the performance of these procedures was found to be approximately equal, and it is concluded that the cost is approximately equal.

The conclusion drawn from the consideration of alternative plastic limit determination methods is that they are equal in reliability and cost. It would seem to be a matter of the preference of the individual laboratory or operator as to which method should be used.

Moisture-Density Relationship of Soils

Results of the comparisons between the one-point compaction method and the standard compaction method are shown in Table 1. It is seen that for both the Indiana and the Ohio typical curves the standard deviation of the differences is approximately 1.4 for the OMC and 2.0 for the MDD.

Hampton has shown the error of measurement for OMC and MDD as determined by the standard method to be 0.702 and 1.01 respectively (10). The one-point method result is seen to vary from the standard method result approximately 30 percent of the time by an amount equal to or greater than 2.0 percentage points for OMC and 2.0 pcf for the MDD.

The one-point OMC was within $\pm$ 3 percentage points of the standard 95 percent of the time and the one-point MDD was within 4.5 pcf of standard 95 percent of the time. The standard deviations and 95 percent values were independent of whether the Ohio typical curves or the Indiana typical were used. The mean difference, however, varied somewhat with respect to typical curves used. The mean difference for both the OMC and the MDD was seen to lie closer to zero when the Indiana curves were used. While the use of either set of typical curves yielded values for OMC which were higher than standard and for MDD which were lower than standard, the Indiana set provided the more accurate results.

The one-point method is formulated on the hypothesis that similar soils result in similar moisture-density curves. The families of curves used in the one-point procedure have been developed by averaging a large number of soil samples of glacial origin. The fine grained soils grouped themselves around the lower curves in the family while those materials with a large percentage of coarse material form the upper curves. Materials which display uniform size, such as a dune sand, generally display a MDD which is lower than the OMC

would indicate and will appear below and to the left of the typical curves. For this reason care must be taken to use the one-point compaction method only on those soils to which it is applicable. Some samples may have been included in the comparison study for which the method was not applicable, thereby making the method appear less reliable.

The conclusion drawn on the basis of the comparison study and the foregoing considerations of soil type is that the one-point compaction is a reliable procedure for glacial soils. Since a large portion of the soil in the state of Indiana is of glacial origin, the method should find wide applicability.

During the six-month period of December 1961 through March 1963, personnel of the JHRP laboratory performed 114 compaction tests according to the standard procedure. The cost of this testing, exclusive of preparation and calculation time, was $431.78 for an average unit cost of $3.79. During the period of September 1962 through March 1963, 66 one-point compaction tests were performed at a total cost of $87.32 or an average unit cost of $1.32. The use of the one-point procedure is seen to have reduced the unit cost by $2.47.

The combined consideration of the accuracy of the standard procedure, the accuracy of the one-point procedure, and the reduction in unit cost, enhance the desirability of the one-point compaction procedure.

Table 2, presents regression equations for the estimation of the OMC and MDD as functions of the classification properties. The equations for the A-, B- and C-horizon soils

yield a standard error of estimate for both the OMC and the MDD of approximately 1.5. The equation for the MDD of non-plastic soils yields an estimate which is slightly less reliable. The use of these equations yields results as reliable as the one-point compaction procedure.

It is concluded that either the one-point compaction procedure or the regression equations provide a rapid method for determining reasonably accurate values for OMC and MDD.

The stepwise regression equations given in Appendix A provide the relationship between the MDD and OMC over the range of values normally encountered in the JHRP laboratory. These relationships correspond to the "line of optimums" in a family of typical compaction curves and are shown in Figure 13. The A-, B-, and C-horizon lines of optimums follow quite closely the Indiana typical curves line of optimums. The steepness of the nonplastic line of optimums is due to the large number of dune sands included in the nonplastic soils. As noted earlier, these soils have both low OMC and low MDD.

In all the equations of Appendix A the minimum standard error is seen to occur before all the independent variables have been utilized. The high degree of correlation between some of the independent variables themselves, as shown in Tables 7, 8, 9, and 10, made it unnecessary to include all the independent variables to obtain the best prediction equation. For example, the PI is a function of the PL and LL, and the GI is highly correlated with LL. These interactions

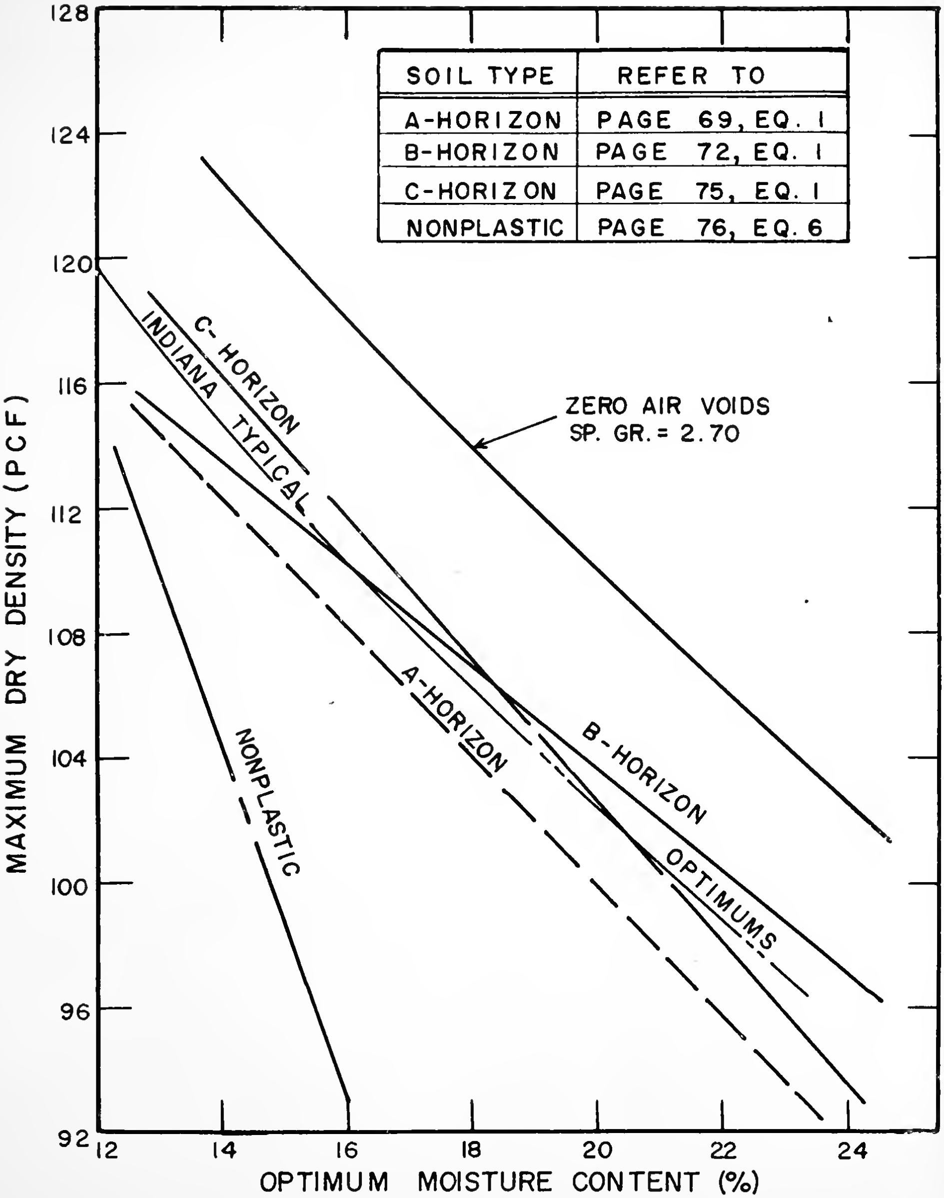


FIG. 13 OPTIMUM MOISTURE CONTENT VS. MAXIMUM DRY DENSITY — REGRESSION LINES

complicate the regression and in the later stages of the stepwise procedure tend to increase rather than decrease the standard error.

In summary it can be stated that a high degree of correlation exists between the moisture-density relationship of a soil and the properties of the soil as expressed by the classification parameters. These classification parameters can be used directly to obtain reliable values for OMC and MDD.

California Bearing Ratio

The California Bearing Ratio, or CBR, is a soil strength parameter which compares the penetration resistance of a given soil with that of a typical well graded granular material. It is a penetration resistance value which is largely effected by shearing resistance of the material. The CBR values obtained are affected by the soil properties as well as mold size, soaking time, surcharge, etc. The U. S. Army Corps of Engineers has performed a rigorous study of the effect of the above properties (21). In tests which were used in this study a mold 6 inches in diameter and 4.5 inches high was used in conjunction with a four day soaking period and a 35 pound soaking and testing surcharge. The fact that these test parameters were held constant for all tests validates the assumption that the variability in the CBR values is due to either error of measurement or to differences in soil type.

The maximum soaked CBR for a given soil sample has been shown to occur when that sample is compacted into the mold at

optimum moisture content (24). The determination of the maximum CBR used in this project was accomplished by compacting one sample at the optimum moisture content and performing the penetration test on this sample after a four day soaking period. The combined operator error obtained in the performance of the compaction control test and in the preparation of the CBR specimen bring about unavoidable discrepancies between the optimum and the molded conditions. This discrepancy, in conjunction with the error of measurement associated with the penetration test, cause added variability in the CBR results. This variability has been lumped together and expressed quantitatively as the standard error of CBR measurement.

Estimates were obtained of the standard error of CBR measurement for each of the three soil types studied. The clay soil yielded an estimate for the standard error of measurement of 1.30 percentage points. At the other extreme, the gravel yielded an estimate of 5.32. The silty clay soil resulted in an estimate of 4.40 for the standard error of measurement.

All CBR variability not attributable to the error of measurement has been assumed to be caused by differences in soil type. Soil type is defined by the classification properties and the average relationships between the soil type and the CBR have been developed by the multiple regression technique. Since all the CBR data used in the regression analysis were obtained by the utilization of procedures having

the error of measurement as discussed previously, the standard error of estimate associated with the regression equation could not be significantly smaller than the standard error of measurement. Assuming the A- and C-horizon soils were represented by the silty clay, the B-horizon soils by the clay, and the nonplastic soils by the gravel, a direct comparison has been made between the standard error of estimate of the regression equations of Table 6 and the standard error of CBR measurement. This comparison is presented in Table 9.

The error associated with the regression equations is nearly equal to that associated with the test procedure for the A-, B-, and C-horizon soils and slightly larger for the nonplastic soils. While the reliability of the regression equations for the nonplastic soils is lower, these soils usually yield CBR values which are higher and less critical from the standpoint of design.

TABLE 11. COMPARISON OF REGRESSION ERROR OF ESTIMATE AND ERROR OF TESTING MEASUREMENT -- CBR

Soil Group	Error of Estimate (Percentage Points)	Error of Measurement (Percentage Points)
A-Horizon	3.4	4.4
B-Horizon	2.6	1.3
C-Horizon	3.9	4.4
Nonplastic	9.1	5.3

The close aggreement between the error of estimate and the error of measurement indicates that a CBR value estimated

with the regression equations of Table 6 is as reliable a value as that obtained from a single penetration test performed on a single sample of a plastic soil. The magnitude of the standard error of estimate associated with the equations of Table 6 indicates that a considerable amount of error will be associated with their use. The error of measurement, however, is also large and indicates that from the standpoint of the testing procedure alone, several CBR tests should be performed and an average value obtained. Had such a mean value for CBR been used in the developement of the regression equations, more reliable equations would probably have been obtained.

Further evaluation of the regression equations was obtained by comparing the CBR ranges for soil groups of the unified classification system as suggested by the Corps of Engineers (18), with values estimated by the regression equations. The regression equations were applied to typical soils from each unified soil class and the comparison with the Corps of Engineers range is given in Table 12.

The CBR values estimated by the regression equations generally agree with the suggested ranges for the unified classification groups. The discrepancies that do exist are for the gravel soils and the estimate for these is considerably lower than the suggested range. The agreement for the fine grained soils, which are most critical in design is generally quite good. The conclusion is that the regression equations yield "reasonable" estimates of CBR for the plastic soils.

TABLE 12. COMPARISON OF REGRESSION CBR WITH CORPS OF ENGINEERS SUGGESTED CBR RANGE FOR UNIFIED SOIL CLASSIFICATION SYSTEM

Unified Class	Regression CBR for Typical Soils* (%)	Corps of Engineers Suggested CBR Range (%)
GW	**	>60
SW	25-35	20-40
GP	**	25-60
SP	28-32	10-25
GM	**	>20
SM	10-28	10-40
GC	**	20-40
SC	2-10	10-20
ML	5-10	5-15
MH	4-6	<8
CL	9-12	5-15
CH	4-6	<4

*Values predicted with equations of Table 6 using typical properties of soils of each class.

**No applicable regression formula available.

The relationships between individual soil properties, optimum moisture content, maximum dry density, and California Bearing Ratio are given in the form of simple correlation coefficients in Tables 7, 8, 9, and 10. A high correlation coefficient indicates that one value could be predicted as a function of the other with a high degree of reliability. The highest degree of correlation is seen to exist between the optimum moisture content and maximum dry density. The linear regression equations expressing this relationship were incorporated in Figure 13. The relationship between CBR and any individual soil property is seen to be weak. This low degree of correlation is reflected in the low degree of reliability of the CBR regression formulas of Table 6. Since the correlation between CBR and an individual property is weak, it is possible for the "best fit" line to assume either a negative or a positive slope and the sign associated with that variable in the regression equation may be different from the sign indicated by engineering judgment. This low degree of correlation with the dependent variable, and the interrelationships between independent variables, complicates the regression analysis and in the later stages of the stepwise procedure often causes changes in the sign of the coefficient of the independent variables as well as increases rather than decreases the standard error of estimate.

This study of the California Bearing Ratio has shown that the error of measurement is quite large but that estimates of CBR can be made on the basis of a knowledge of the

classification properties. A considerable amount of error is associated with these estimates. The equations provide an approximation which is more reliable for plastic soils than nonplastic soils.

SUMMARY

This study considered alternative methods for the determination of the classification, compaction, and CBR properties of soils. Fang's flow index method was shown to be a reliable procedure for the determination of the liquid limit. It was shown that the one-point method is more economical than the standard method.

The squash test for the determination of the plastic limit was shown to be comparable in reliability to the roll-out method but no savings of time or money were evident.

The one-point compaction method utilizing the typical moisture-density curves was seen to be reliable for the soils studied. Regression equations were developed for the estimation of the optimum moisture content and maximum dry density as functions of the classification properties.

Study of the error of measurement associated with the California Bearing Ratio showed this value to be quite high. Regression equations for the prediction of the CBR as functions of the classification properties were developed and shown to provide CBR approximations which were reliable for the plastic soils studied.

PROPOSED RESEARCH

Consideration of the routine soil tests and the relationship among soil type, compaction characteristics, and California Bearing Ratio, has indicated a need for further research in two respects.

First, a more thorough knowledge of the validity of the routine tests to be used in conjunction with quality control type specifications is needed. The error of measurement for each test should be determined and this error used in conjunction with confidence limits to establish acceptable ranges for control specifications.

Second, developement of a concise, quantitative expression for soil type would greatly facilitate soil classification. Special consideration should be given to formulating a means of expressing the grain size distribution of a soil in a manner which is brief but unique with respect to that soil. Combinations of grain size and plasticity have been used to classify soils into broad categories but greater refinement is desirable.

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APPENDIX A

Summary of Regression Equations for Optimum Moisture Content and Maximum Dry Density

NOTATION

The symbols used in the tables in this section and not previously defined have the following meaning:

MDD = Maximum Dry Density (pcf)

OMC = Optimum Moisture Content (%)

PL = Plastic Limit (%)

LL = Liquid Limit (%)

PI = Plasticity Index (%)

G = Percent of material retained on a No. 40 sieve (%)

S = Percent of material passing a No. 40 sieve but larger than 0.05 mm (%)

F = Percent of material smaller than 0.05 mm (%)

GI = Group Index defined according to the AASHO Classification System

FA = Fineness average determined by taking one-sixth of the total percentages, by weight, of the following sizes: No. 10 sieve, No. 40 sieve, No. 200 sieve, 0.02 mm, 0.005 mm, and 0.001 mm.

N = Nonplastic soil problems indication. N designates whether any of the Atterberg limits were obtainable. N = 1 if any limit measurable. N = 2 if no limit measurable.

R = Multiple Correlation Coefficient

TABLE 13 . A-HORIZON REGRESSION RESULTS: MAXIMUM DRY DENSITY ON SOIL CLASSIFICATION PROPERTIES

Regression Equation	Std. Error	R^2
MDD = 125.99 - 0.98PL	3.42	0.580
MDD = 126.87 - 0.64PL - 0.26LL	3.17	0.645
MDD = 126.05 - 0.64PL - 0.27LL + 0.24G	3.03	0.682
MDD = 120.02 - 0.61PL - 0.30LL + 0.30G + 0.10FA	3.02	0.690
MDD = 112.77 - 0.50PL - 0.36LL + 0.31G + 0.33FA - 0.11F	2.93	0.714
MDD = 115.97 - 0.36PL - 0.54LL + 0.30G + 0.34FA - 0.17F + 0.50GI	2.89	0.726
MDD = 221.07 - 0.37PL - 0.54LL - 0.75G + 0.32FA - 1.21F + 0.51GI - 1.04S	2.92	0.727
MDD = 221.17 - 0.09PL - 0.82LL - 0.75G + 0.32FA - 1.21F + 0.51GI - 1.04S + 0.28PI	2.95	0.728

TABLE 14 . A-HORIZON REGRESSION RESULTS: OPTIMUM MOISTURE CONTENT ON SOIL CLASSIFICATION PROPERTIES

Regression Equation	Std. Error	R^2
OMC = 9.61 + 0.26LL	1.93	0.506
OMC = 10.24 + 0.27LL - 0.19G	1.78	0.589
OMC = 7.56 + 0.16LL - 0.19G + 0.27PL	1.62	0.665
OMC = 7.67 + 0.22LL - 0.21G + 0.24PL - 0.14GI	1.61	0.673
OMC = 5.18 + 0.29LL - 0.19G + 0.18PL - 0.34GI + 0.04F	1.59	0.712
OMC = 10.36 + 0.33LL - 0.21G + 0.13PL - 0.35GI + 0.08F - 0.12FA	1.57	0.732
OMC = 6.02 + 0.32LL - 0.17G + 0.13PL - 0.35GI + 0.12F - 0.12FA + 0.04S	1.58	0.732
OMC = 6.11 + 0.08LL - 0.17G + 0.38PL - 0.35GI + 0.12F - 0.12FA + 0.04S + 0.25PI	1.60	0.733

TABLE 15 . A-HORIZON REGRESSION RESULTS: MAXIMUM DRY DENSITY ON SOIL CLASSIFICATION PROPERTIES AND OPTIMUM MOISTURE CONTENT

Regression Equation	Std. Error	R^2
MDD = 135.60 - 1.770MC	2.08	0.845
MDD = 136.95 - 1.420MC - 0.32PL	1.86	0.877
MDD = 135.41 - 1.440MC - 0.32PL + 0.03FA	1.88	0.886
MDD = 132.80 - 1.440MC - 0.31PL + 0.11FA - 0.04F	1.86	0.882
MDD = 131.02 - 1.360MC - 0.24PL + 0.15FA - 0.06F - 0.07LL	1.85	0.885
MDD = 131.25 - 1.360MC - 0.23PL + 0.15FA - 0.06F - 0.09LL + 0.04GI	1.87	0.886
MDD = 132.38 - 1.340MC - 0.23PL + 0.16FA - 0.08F - 0.10LL + 0.05GI - 0.02S	1.90	0.885
MDD = 238.79 - 1.340MC - 0.24PL + 0.15FA - 1.14F - 0.09LL + 0.06GI - 1.07S - 1.07G	1.90	0.894
MDD = 239.18 - 1.340MC + 0.83PL + 0.15FA - 1.14F - 1.16LL + 0.06GI - 1.08S - 1.07G + 1.07PI	1.92	0.886

TABLE 16 . B-HORIZON REGRESSION RESULTS: MAXIMUM DRY DENSITY ON SOIL CLASSIFICATION PROPERTIES

Regression Equation	Std. Error	R^2
MDD = 128.42 - 0.50LL	3.04	0.662
MDD = 130.39 - 0.34LL - 0.12F	2.57	0.819
MDD = 124.51 - 0.32LL - 0.08F + 0.09S	2.53	0.826
MDD = 124.69 - 0.31LL - 0.04F + 0.11S - 0.06FA	2.54	0.829
MDD = 127.68 - 0.36LL - 0.05F + 0.10S - 0.09FA + 0.17GI	2.54	0.830
MDD = 128.20 - 0.34LL - 0.04F + 0.10S - 0.10FA + 0.14GI - 0.08PL	2.55	0.831
MDD = 127.99 + 0.32LL - 0.03F + 0.11S - 0.10FA + 0.13GI - 0.71PL - 0.66PI	2.55	0.831
MDD = 153.95 + 0.32LL - 0.29F - 0.15S - 0.10FA + 0.13GI - 0.72PL - 0.66PI - 0.26G	2.57	0.834

TABLE 17 . B-HORIZON REGRESSION RESULTS: OPTIMUM MOISTURE CONTENT ON SOIL CLASSIFICATION PROPERTIES

Regression Equation	Std. Error	R^2
OMC = 12.51 + 0.42GI	1.66	0.682
OMC = 15.58 + 0.30GI - 0.07S	1.56	0.721
OMC = 13.03 + 0.14GI - 0.06S + 0.10LL	1.50	0.744
OMC = 6.00 - 0.09GI - 0.05S + 0.16LL + 0.11FA	1.42	0.773
OMC = 2.83 - 0.07GI - 0.03S + 0.15LL + 0.15FA + 0.04G	1.42	0.777
OMC = - 84.76 - 0.07GI + 0.84S + 0.15LL + 0.15FA + 0.92G + 0.87F	1.43	0.777
OMC = - 90.34 - 0.07GI + 0.90S + 0.15LL + 0.15FA + 0.97G + 0.93F	1.44	0.777
OMC = - 122.40 - 0.06GI + 1.22S - 0.12LL + 0.16FA + 1.30G + 1.25F + 0.27PI	1.44	0.779

TABLE 18 . B-HORIZON REGRESSION RESULTS: MAXIMUM DRY DENSITY ON SOIL CLASSIFICATION PROPERTIES AND OPTIMUM MOISTURE CONTENT

Regression Equation	Std. Error	R^2
MDD = 141.76 - 1.960MC	1.82	0.908
MDD = 140.50 - 1.540MC - 0.14LL	1.62	0.927
MDD = 135.32 - 1.390MC - 0.12LL + 0.07S	1.54	0.937
MDD = 137.25 - 1.380MC - 0.09LL + 0.06S - 0.13PL	1.53	0.937
MDD = 137.10 - 1.390MC + 0.28LL + 0.06S - 0.49PL - 0.37PI	1.53	0.938
MDD = 138.09 - 1.360MC + 0.27LL + 0.04S - 0.48PL - 0.37PI - 0.02F	1.54	0.938
MDD = 137.82 - 1.450MC + 0.17LL - 0.00S - 0.34PL - 0.28PI - 0.10F + 0.13FA	1.50	0.940
MDD = 138.28 - 1.440MC + 0.16LL - 0.00S - 0.34PL - 0.28PI - 0.10F + 0.12FA + 0.03GI	1.51	0.943
MDD = - 23.58 - 1.450MC + 0.14LL + 1.61S - 0.32PL - 0.27PI + 1.52F + 0.12FA + 0.04GI + 1.62G	1.51	0.943

TABLE 19 . O-HORIZON REGRESSION RESULTS: MAXIMUM DRY DENSITY ON SOIL CLASSIFICATION PROPERTIES

Regression Equation	Std. Error	R^2
MDD = 139.48 - 0.80LL	3.58	0.765
MDD = 142.71 - 0.60LL - 0.14F	3.04	0.832
MDD = 144.40 - 0.84LL - 0.12F + 0.34PI	2.98	0.842
MDD = 140.70 - 0.89LL - 0.06F + 0.39PI + 0.10G	2.93	0.848
MDD = 134.48 - 0.87LL - 0.10F + 0.34PI + 0.14G + 0.14FA	2.90	0.853
MDD = 133.31 - 0.85LL - 0.09F + 0.35PI + 0.14G + 0.16FA - 0.16GI	2.92	0.856
MDD = 134.11 - 0.85LL - 0.10F + 0.35PI + 0.13G + 0.16FA - 0.16GI - 0.01S	2.94	0.856
MDD = 134.12 - 4.98LL - 0.10F + 4.48PI + 0.13G + 0.16FA - 0.16GI - 0.01S + 4.13PL	2.96	0.856

TABLE 20 . C-HORIZON REGRESSION RESULTS: OPTIMUM MOISTURE CONTENT ON SOIL CLASSIFICATION PROPERTIES

Regression Equation	Std. Error	R^2
OMC = 3.45 + 0.37LL	1.70	0.755
OMC = 1.36 + 0.57LL - 0.33PI	1.55	0.801
OMC = 2.05 + 0.49LL - 0.30PI + 0.20GI	1.51	0.814
OMC = 2.54 + 0.49LL - 0.30PI + 0.15GI - 0.02G	1.51	0.816
OMC = 3.59 + 0.49LL - 0.30PI + 0.17GI - 0.03G - 0.02FA	1.52	0.817
OMC = 3.68 + 0.49LL - 0.30PI + 0.17GI - 0.03G - 0.02FA - 0.00S	1.53	0.817
OMC = 3.77 + 0.49LL - 0.30PI + 0.17GI - 0.03G - 0.02FA - 0.00S - 0.00F	1.54	0.817
OMC = 3.77 + 0.27LL - 0.08PI + 0.17GI - 0.03G - 0.02FA - 0.00S - 0.00F + 0.21PL	1.55	0.817

TABLE 21 . C-HORIZON REGRESSION RESULTS: MAXIMUM DRY DENSITY ON SOIL CLASSIFICATION PROPERTIES AND OPTIMUM MOISTURE CONTENT

Regression Equation	Std. Error	R^2
MDD = 145.60 - 2.060MO	2.05	0.922
MDD = 146.70 - 1.780MC - 0.08F	1.77	0.942
MDD = 146.12 - 1.630MC - 0.08F - 0.13PI	1.71	0.948
MDD = 144.07 - 1.640MC - 0.05F - 0.13PI + 0.05G	1.69	0.949
MDD = 138.00 - 1.620MC - 0.09F - 0.16PI + 0.09G + 0.14FA	1.62	0.954
MDD = 138.80 - 1.650MC - 0.10F - 0.18PI + 0.09G + 0.13FA + 0.10GI	1.63	0.955
MDD = 138.00 - 1.580MC - 0.09F - 0.12PI + 0.10G + 0.13FA + 0.12GI - 0.07LL	1.64	0.954
MDD = 140.09 - 1.580MC - 0.10F - 0.12PI + 0.09G + 0.13FA + 0.11GI - 0.07LL - 0.01S	1.65	0.955
MDD = 140.10 - 1.580MC - 0.10F + 4.34PI + 0.08G + 0.13FA + 0.11GI - 4.54LL - 0.01S + 4.46PL	1.66	0.955

TABLE 22. NONPLASTIC SOIL REGRESSION RESULTS: MAXIMUM DRY DENSITY ON SOIL CLASSIFICATION PROPERTIES AND OPTIMUM MOISTURE CONTENT.

Regression Equation	Std. Error	R^2
MDD = 128.63 - 0.22S	4.29	0.577
MDD = 126.64 - 0.20S + 0.06F	4.30	0.589
MDD = - 1163.94 + 12.70S + 12.97F + 12.91G	4.32	0.595
MDD = - 1087.90 + 11.97S + 12.29F + 12.16G - 0.10FA	4.38	0.595
MDD = -1083.04 + 11.92S + 12.24F + 12.11G - 0.10FA + 0.14N	4.44	0.596
OMC = 32.8 - 0.18 MDD	1.29	0.463

APPENDIX B

Summary of Regression Equations for California Bearing Ratio

NOTATION

The symbols used in the tables in this section and not previously defined have the following meaning:

γ_d = Molded Dry Density (pcf)

W = Molded Moisture Content (%)

PL = Plastic Limit (%)

LL = Liquid Limit (%)

PI = Plasticity Index (%)

G = Percent of material retained on a No. 40 sieve (%)

S = Percent of material passing a No. 40 sieve but larger than 0.05 mm (%)

F = Percent of material smaller than 0.05 mm (%)

GI = Group Index defined according to the AASHO Classification System

FA = Fineness average determined by taking one-sixth of the total percentags, by weight, of the following: No. 10 sieve, No. 40 sieve, No. 200 sieve, 0.02 mm, 0.005 mm, and 0.001 mm.

CBR = 0.1" California Bearing Ratio (%)

R = Multiple Correlation Coefficient.

TABLE 23a. A-HORIZON REGRESSION RESULTS: CALIFORNIA BEARING RATIO ON SOIL CLASSIFICATION PROPERTIES - PROBLEM NO. 1

Regression Equation	Std. Error	R^2
$CBR = 18.72 - 0.60w$	3.75	0.166
$CBR = 96.88 - 1.61w - 0.58\gamma_d$	3.57	0.260
$CBR = 98.59 - 1.66w - 0.57\gamma_d - 0.09S$	3.40	0.342
$CBR = 80.46 - 1.68w - 0.44\gamma_d - 0.09S + 0.23PL$	3.37	0.363
$CBR = 85.37 - 1.66w - 0.47\gamma_d - 0.11S + 0.24PL - 0.23GI$	3.36	0.379
$CBR = 81.97 - 1.75w - 0.51\gamma_d - 0.08S + 0.28PL - 0.30GI + 0.13FA$	3.36	0.390
$CBR = 80.15 - 1.72w - 0.53\gamma_d - 0.07S + 0.26PL - 0.33GI + 0.18FA + 0.09G$	3.38	0.395
$CBR = 80.75 - 1.76w - 0.52\gamma_d - 0.08S + 0.22PL - 0.43GI + 0.17FA + 0.06G + 0.06LL$	3.41	0.396
$CBR = 78.24 - 1.68w - 0.52\gamma_d - 0.08S - 4.64PL - 0.46GI + 0.19FA + 0.08G + 4.91LL - 4.86PI$	3.41	0.410
$CBR = -4.31 - 1.66w - 0.51\gamma_d + 0.73S - 4.68PL - 0.46GI + 0.20FA + 0.90G + 4.95LL - 4.90PI + 0.81F$	3.44	0.411

TABLE 23b. A-HORIZON REGRESSION RESULTS: CALIFORNIA BEARING RATIO ON SOIL CLASSIFICATION PROPERTIES - PROBLEM NO. 2

Regression Equation	Std. Error	R^2
$\log CBR = 1.535 - 0.039w$	0.220	0.193
$\log CBR = 1.402 - 0.073w + 0.032PL$	0.202	0.335
$\log CBR = 4.686 - 0.107w + 0.025PL - 0.024\gamma_d$	0.198	0.372
$\log CBR = 4.856 - 0.109w + 0.023PL - 0.024\gamma_d - 0.004S$	0.194	0.408
$\log CBR = 4.758 - 0.110w + 0.024PL - 0.025\gamma_d - 0.003S + 0.002FA$	0.196	0.409
$\log CBR = 4.825 - 0.111w + 0.024PL - 0.026\gamma_d - 0.003S + 0.004FA - 0.005GI$	0.197	0.411
$\log CBR = 4.823 - 0.114w + 0.020PL - 0.025\gamma_d - 0.004S + 0.004FA - 0.018GI + 0.007LL$	0.198	0.418
$\log CBR = 4.672 - 0.108w - 0.363PL - 0.025\gamma_d - 0.005S + 0.004FA - 0.022GI + 0.390LL - 0.382PI$	0.196	0.443
$\log CBR = 4.614 - 0.107w - 0.373PL - 0.025\gamma_d - 0.004S + 0.006FA - 0.020GI + 0.398LL - 0.392PI + 0.002G$	0.198	0.443
$\log CBR = -0.796 - 0.106w - 0.375PL - 0.025\gamma_d + 0.049S + 0.006FA - 0.020GI + 0.401LL - 0.395PI + 0.056G + 0.053F$	0.200	0.444

TABLE 23c. A-HORIZON REGRESSION RESULTS: CALIFORNIA BEARING RATIO ON SOIL CLASSIFICATION PROPERTIES - PROBLEM NO. 3

Regression Equation	Std. Error	R^2
$\log CBR = 2.95 - 1.69\log w$	0.220	0.193
$\log CBR = 2.24 - 3.25\log w + 1.95\log PL$	0.200	0.369
$\log CBR = 2.73 - 3.31\log w + 1.84\log PL - 0.20\log S$	0.195	0.388
$\log CBR = 15.10 - 4.59\log w + 1.39\log PL - 0.22\log S - 5.02\log \gamma_d$	0.192	0.420
$\log CBR = 14.64 - 4.66\log w + 1.30\log PL - 0.22\log S - 4.85\log \gamma_d + 0.20\log LL$	0.194	0.422
$\log CBR = 15.22 - 4.61\log w - 0.93\log PL - 0.22\log S - 5.40\log \gamma_d + 3.07\log LL - 0.87\log PI$	0.192	0.443
$\log CBR = 15.44 - 4.63\log w - 1.21\log PL - 0.25\log S - 5.52\log \gamma_d + 3.47\log LL - 0.96\log PI - 0.07\log GI$	0.193	0.446
$\log CBR = 15.31 - 4.71\log w - 1.17\log PL - 0.25\log S - 5.47\log \gamma_d + 3.52\log LL - 0.97\log PI - 0.07\log GI - 0.02\log G$	0.195	0.447
$\log CBR = 14.93 - 4.78\log w - 1.19\log PL - 0.19\log S - 5.53\log \gamma_d + 3.62\log LL - 0.97\log PI - 0.12\log GI - 0.02\log G + 0.24\log F$	0.197	0.447
$\log CBR = 15.05 - 4.77\log w - 1.24\log PL - 0.20\log S - 5.46\log \gamma_d + 3.69\log LL - 0.99\log PI - 0.11\log GI - 0.02\log G + 0.27\log F - 0.20\log FA$	0.199	0.448

TABLE 23d. A-HORIZON REGRESSION RESULTS: CALIFORNIA BEARING RATIO ON SOIL CLASSIFICATION PROPERTIES - PROBLEM NO. 4

Regression Equation	Std. Error	R^2
$CBR = 18.72 - 0.60w$	3.75	0.167
$CBR = 27.01 - 0.69w - 5.49 \log S$	3.48	0.294
$CBR = 103.10 - 1.67w - 5.39 \log S - 0.56 \gamma_d$	3.27	0.389
$CBR = 71.11 - 1.69w - 5.05 \log S - 0.44 \gamma_d + 13.71 \log PL$	3.26	0.403
$CBR = 90.74 - 1.66w - 7.52 \log S - 0.44 \gamma_d + 12.15 \log PL - 7.54 \log F$	3.28	0.407
$CBR = 97.00 - 1.61w - 7.52 \log S - 0.47 \gamma_d + 10.22 \log PL - 7.74 \log F - 1.75 \log PI$	3.28	0.422
$CBR = 82.04 - 1.65w - 7.23 \log S - 0.50 \gamma_d + 10.56 \log PL - 12.66 \log F - 2.32 \log PI + 15.65 \log FA$	3.29	0.429
$CBR = 99.85 - 1.60w - 8.68 \log S - 0.49 \gamma_d + 8.19 \log PL - 19.36 \log F - 3.21 \log PI + 13.96 \log FA + 2.01 \log GI$	3.31	0.434
$CBR = 91.86 - 1.59w - 7.96 \log S - 0.50 \gamma_d + 7.78 \log PL - 17.33 \log F - 3.30 \log PI + 16.72 \log FA + 1.59 \log GI + 0.04G$	3.33	0.437
$CBR = 92.92 - 1.59w - 7.90 \log S - 0.50 \gamma_d + 6.50 \log PL - 16.88 \log F - 3.73 \log PI + 16.47 \log FA + 1.48 \log GI + 0.04G + 0.02LL$	3.37	0.437

[illegible]

[illegible]	[illegible]	[illegible]

TABLE 23e. A-HORIZON REGRESSION RESULTS: CALIFORNIA BEARING RATIO ON SOIL CLASSIFICATION PROPERTIES - PROBLEM NO. 5

Regression Equation	Std. Error	R^2
$CBR = 40.88 - 26.41 \log w$	3.75	0.193
$CBR = 53.58 - 30.83 \log w - 5.76 \log S$	3.48	0.335
$CBR = 165.20 - 73.29 \log w - 5.96 \log S - 0.56\gamma_d$	3.27	0.372
$CBR = 149.42 - 73.54 \log w - 5.75 \log S - 0.45\gamma_d + 0.19PL$	3.26	0.408
$CBR = 150.53 - 72.33 \log w - 5.70 \log S - 0.47\gamma_d + 0.18PL - 0.05PI$	3.28	0.409
$CBR = 103.41 - 77.01 \log w - 5.68 \log S - 0.48\gamma_d - 0.30PL - 0.57PI + 46.35 \log LL$	3.28	0.411
$CBR = 114.18 - 75.81 \log w - 8.02 \log S - 0.48\gamma_d - 0.39PL - 0.64PI + 52.00 \log LL - 7.78 \log F$	3.29	0.418
$CBR = 115.46 - 77.56 \log w - 7.79 \log S - 0.51\gamma_d - 0.42PL - 0.70PI + 55.65 \log LL - 11.69 \log F + 0.10FA$	3.31	0.443
$CBR = 126.83 - 75.41 \log w - 9.37 \log S - 0.50\gamma_d - 0.47PL - 0.76PI + 57.07 \log LL - 19.68 \log F + 0.10FA + 2.19 \log GI$	3.33	0.443
$CBR = 126.32 - 75.25 \log w - 9.32 \log S - 0.51\gamma_d - 0.48PL - 0.77PI + 57.20 \log LL - 19.56 \log F + 0.11FA + 2.13 \log GI + 0.08 \log G$	3.37	0.444

TABLE 24a. B-HORIZON REGRESSION RESULTS: CALIFORNIA BEARING RATIO ON SOIL CLASSIFICATION PROPERTIES - PROBLEM NO. 1

Regression Equation	Std. Error	R^2
CBR = 3.45 + 0.24w	3.69	0.197
CBR = 7.89 + 0.26w - 0.22PI	3.24	0.392
CBR = 9.32 + 0.26w - 0.16PI - 0.04F	3.21	0.410
CBR = 13.99 + 0.10w - 0.33PI - 0.09F + 0.48GI	3.12	0.448
CBR = 12.24 - 0.01w - 0.50PI - 0.09F + 0.43GI + 0.18LL	3.11	0.458
CBR = 16.45 - 0.59w - 1.53PI + 0.01F + 0.16GI + 1.43LL - 1.36PL	2.85	0.549
CBR = 48.78 - 0.92w - 1.57PI - 0.01F + 0.18GI + 1.45LL - 1.42PL - 0.23γ_d	2.84	0.553
CBR = 54.98 - 1.10w - 1.64PI - 0.06F + 0.06GI + 1.54LL - 1.46PL - 0.31γ_d + 0.15FA	2.82	0.571
CBR = 65.54 - 1.23w - 1.62PI - 0.16F + 0.09GI + 1.49LL - 1.44PL - 0.34γ_d + 0.24FA - 0.11S	2.79	0.585
CBR = 187.11 - 1.42w + 0.35PI - 1.45F + 0.05GI - 0.41LL + 0.48PL - 0.28γ_d + 0.28FA - 1.40S - 1.28G	2.63	0.636

TABLE 24b. B-HORIZON REGRESSION RESULTS: CALIFORNIA BEARING RATIO ON SOIL CLASSIFICATION PROPERTIES - PROBLEM NO. 2

Regression Equation	Std. Error	R^2
$\log CBR = 0.985 - 0.006PI$	0.181	0.067
$\log CBR = 0.802 - 0.017PI + 0.010LL$	0.174	0.146
$\log CBR = 0.958 - 0.018PI + 0.014LL - 0.014PL$	0.172	0.175
$\log CBR = 1.137 - 0.060PI + 0.061LL - 0.052PL - 0.028w$	0.164	0.259
$\log CBR = 1.007 - 0.079PI + 0.079LL - 0.072PL - 0.040w + 0.006FA$	0.159	0.312
$\log CBR = 3.481 - 0.085PI + 0.084LL - 0.081PL - 0.067w + 0.006FA - 0.017\gamma_d$	0.157	0.344
$\log CBR = 3.769 - 0.083PI + 0.081LL - 0.076PL - 0.070w + 0.010FA - 0.020\gamma_d - 0.002F$	0.157	0.345
$\log CBR = 3.943 - 0.083PI + 0.081LL - 0.076PL - 0.073w + 0.011FA - 0.021\gamma_d - 0.004F - 0.002S$	0.158	0.346
$\log CBR = 10.370 + 0.022PI - 0.021LL + 0.026PL - 0.083w + 0.013FA - 0.018\gamma_d - 0.072F - 0.070S - 0.068G$	0.150	0.415
$\log CBR = 10.370 + 0.022PI - 0.022LL + 0.026PL - 0.082w + 0.013FA - 0.017\gamma_d - 0.072F - 0.070S - 0.067G + 0.002GI$	0.151	0.416

TABLE 24c. B-HORIZON REGRESSION RESULTS: CALIFORNIA BEARING RATIO ON SOIL CLASSIFICATION PROPERTIES - PROBLEM NO. 3

Regression Equation	Std. Error	R^2
logCBR = 1.95 -0.89logw	0.159	0.159
logCBR = 1.03 -1.77logw +1.13logFA	0.145	0.312
logCBR = 17.14 -3.71logw +1.08logFA -6.71logγ_d	0.136	0.396
logCBR = 16.62 -3.59logw +1.48logFA -6.84logγ_d -0.09logGI	0.134	0.419
logCBR = 12.82 -3.69logw +1.62logFA -5.40logγ_d -0.13logGI +0.49logLL	0.133	0.441
logCBR = 13.09 -3.73logw +1.53logFA -5.36logγ_d -0.12logGI +0.43logLL -0.06logS	0.133	0.445
logCBR = 14.07 -3.80logw +1.78logFA -5.74logγ_d -0.10logGI +0.39logLL -0.09logS -0.27logF	0.134	0.447
logCBR = 13.61 -3.77logw +1.87logFA -5.61logγ_d -0.09logGI +0.29logLL -0.09logS -0.35logF +0.24logPL	0.134	0.450
logCBR = 13.90 -3.79logw +1.95logFA -5.58logγ_d -0.10logGI -0.84logLL -0.10logS -0.40logF +0.74logPL +0.56logPI	0.135	0.453
logCBR = 13.90 -3.79logw +1.95logFA -5.58logγ_d -0.10logGI -0.84logLL -0.10logS -0.39logF +0.79logPL +0.56logPI +0.00logG	0.135	0.453

TABLE 24d: B-HORIZON REGRESSION RESULTS: CALIFORNIA BEARING RATIO ON SOIL CLASSIFICATION PROPERTIES - PROBLEM NO. 4

Regression Equation	Std. Error	R^2
CBR = 17.29 -0.54w	2.70	0.276
CBR = -0.43 -0.79w +12.30logFA	2.61	0.338
CBR = -39.68 -0.96w +35.11logFA +0.18G	2.52	0.397
CBR = -55.84 -0.87w +44.43logFA +0.17G -2.24logGI	2.45	0.436
CBR = -15.07 -1.46w +46.74logFA +0.19G -2.62logGI -0.32γ_d	2.38	0.488
CBR = -30.47 -1.43w +47.01logFA +0.18G -2.80logGI -0.26γ_d +6.17logPL	2.38	0.495
CBR = -27.75 -1.46w +51.01logFA +0.17G -2.53logGI -0.28γ_d +7.25logPL -4.51logF	2.39	0.498
CBR = -13.90 -1.50w +50.65logFA +0.14G -2.12logGI -0.30γ_d +6.58logPL -9.04logF -1.45logS	2.40	0.504
CBR = -9.56 -1.50w +50.96logFA +0.14G -1.91logGI -0.32γ_d +6.67logPL -9.90logF -1.61logS -1.00logPI	2.41	0.504
CBR = -3.53 -1.50w +49.20logFA +0.15G -1.84logGI -0.32γ_d +3.60logPL -8.52logF -1.40logS -3.87logPI +0.06LL	2.42	0.506

TABLE 24e. B-HORIZON REGRESSION RESULTS: CALIFORNIA BEARING RATIO ON SOIL CLASSIFICATION PROPERTIES - PROBLEM NO. 5

Regression Equation	Std. Error	R^2
$CBR = 34.61 - 21.65\log w$	2.66	0.067
$CBR = 42.41 - 34.30\log w + 0.12FA$	2.54	0.146
$CBR = 124.47 - 64.32\log w + 0.12FA - 0.41\gamma_d$	2.44	0.175
$CBR = 122.80 - 63.42\log w + 0.19FA - 0.43\gamma_d - 1.88\log GI$	2.39	0.259
$CBR = 124.09 - 63.88\log w + 0.17FA - 0.41\gamma_d - 1.72\log GI - 1.29\log S$	2.39	0.312
$CBR = 135.75 - 65.95\log w + 0.21FA - 0.44\gamma_d - 1.28\log GI - 1.65\log S - 4.76\log F$	2.40	0.344
$CBR = 130.01 - 65.42\log w + 0.21FA - 0.41\gamma_d - 1.36\log GI - 1.38\log S - 5.07\log F + 0.09PL$	2.40	0.345
$CBR = 129.62 - 65.72\log w + 0.21FA - 0.41\gamma_d - 1.41\log GI - 1.38\log S - 4.62\log F + 0.08PL + 0.11\log G$	2.42	0.346
$CBR = 132.07 - 65.74\log w + 0.22FA - 0.42\gamma_d - 1.33\log GI - 1.44\log S - 4.97\log F + 0.09PL + 0.12\log G - 0.77\log LL$	2.43	0.415
$CBR = 137.92 - 65.29\log w + 0.20FA - 0.42\gamma_d - 1.24\log GI - 1.44\log S - 4.34\log F + 0.15PL + 0.14\log G - 6.53\log LL + 0.06PI$	2.45	0.416

TABLE 25a. C-HORIZON REGRESSION RESULTS: CALIFORNIA BEARING RATIO ON SOIL CLASSIFICATION PROPERTIES - PROBLEM NO. 1

Regression Equation	Std. Error	R^2
CBR = 9.22 - 0.12G	4.97	0.062
CBR = 13.04 - 0.17G - 0.30PI	4.75	0.155
CBR = 15.60 - 0.14G - 0.37PI - 0.09S	4.66	0.198
CBR = 23.36 - 0.18G - 0.17PI - 0.13S - 0.60w	4.52	0.256
CBR = 17.07 - 0.17G - 0.07PI - 0.08S - 1.41w + 0.88PL	4.18	0.373
CBR = 36.34 - 0.33G - 0.01PI - 0.14S - 1.44w + 0.91PL - 0.29FA	4.05	0.420
CBR = 92.91 - 0.27G - 0.05PI - 0.12S - 2.10w + 0.88PL - 0.26FA - 0.42γ_d	3.96	0.453
CBR = 94.04 - 0.28G + 0.07PI - 0.14S - 2.04w + 0.94PL - 0.18FA - 0.45γ_d - 0.61GI	3.89	0.479
CBR = 88.71 - 0.25G + 0.08PI - 0.11S - 2.01w + 0.92PL - 0.21FA - 0.43γ_d - 0.64GI + 0.05F	3.91	0.484
CBR = 88.73 - 0.25G + 3.89PI - 0.11S - 2.01w + 4.73PL - 0.21FA - 0.43γ_d - 0.64GI + 0.05F - 3.81LL	3.94	0.483

TABLE 25b. O-HORIZON REGRESSION RESULTS: CALIFORNIA BEARING RATIO ON SOIL CLASSIFICATION PROPERTIES - PROBLEM NO. 2

Regression Equation	Std. Error	R^2
logCBR = 0.923 -0.011PI	0.258	0.046
logCBR = 0.679 -0.018PI +0.005F	0.245	0.150
logCBR = 0.895 -0.006PI +0.009F -0.042w	0.232	0.253
logCBR = 0.763 -0.000PI +0.006F -0.082w +0.044PL	0.215	0.365
logCBR = 4.438 -0.003PI +0.004F -0.122w +0.045PL -0.025γ_d	0.209	0.410
logCBR = 4.908 -0.003PI +0.002F -0.124w +0.043PL -0.027γ_d -0.003S	0.208	0.421
logCBR = 5.197 -0.003PI +0.005F -0.122w +0.046PL -0.024γ_d -0.008S -0.010G	0.204	0.457
logCBR = 5.138 +0.001PI -0.002F -0.117w +0.046PL -0.020γ_d -0.008S -0.014G -0.012FA	0.200	0.481
logCBR = 5.084 +0.004PI -0.001F -0.115w +0.047PL -0.020γ_d -0.008S -0.014G -0.010FA -0.016GI	0.201	0.488
logCBR = 5.085 +0.258PI -0.001F -0.115w +0.300PL -0.020γ_d -0.008S -0.014G -0.010FA -0.016GI -0.253LL	0.202	0.488

TABLE 25c. C-HORIZON REGRESSION RESULTS: CALIFORNIA BEARING RATIO ON SOIL CLASSIFICATION PROPERTIES - PROBLEM NO. 3

Regression Equation	Std. Error	R^2
$\log CBR = 0.90 - 0.11\log G$	0.252	0.093
$\log CBR = 2.78 - 0.23\log G - 1.59\log w$	0.223	0.297
$\log CBR = 2.07 - 0.20\log G - 2.60\log w + 1.49\log PL$	0.209	0.391
$\log CBR = 2.87 - 0.16\log G - 2.72\log w + 1.23\log PL - 0.27\log S$	0.206	0.419
$\log CBR = 2.90 - 0.17\log G - 3.16\log w + 1.02\log PL - 0.27\log S + 0.50\log LL$	0.205	0.430
$\log CBR = 7.84 - 0.16\log G - 3.69\log w + 1.02\log PL - 0.29\log S + 0.48\log LL - 2.08\log \gamma_d$	0.206	0.436
$\log CBR = 7.69 - 0.14\log G - 3.77\log w + 1.06\log PL - 0.27\log S + 0.46\log LL - 2.12\log \gamma_d + 0.15\log F$	0.207	0.439
$\log CBR = 7.65 - 0.14\log G - 3.79\log w + 0.85\log PL - 0.26\log S + 0.82\log LL - 2.16\log \gamma_d + 0.16\log F - 0.13\log PI$	0.208	0.439
$\log CBR = 7.50 - 0.14\log G - 3.76\log w + 0.71\log PL - 0.24\log S + 1.06\log LL - 2.07\log \gamma_d + 0.36\log F - 0.22\log PI - 0.32\log FA$	0.210	0.440
$\log CBR = 7.49 - 0.14\log G - 3.75\log w + 0.72\log PL - 0.24\log S + 1.06\log LL - 2.03\log \gamma_d + 0.32\log F - 0.22\log PI - 0.32\log FA + 0.01\log GI$	0.211	0.440

TABLE 25d. C-HORIZON REGRESSION RESULTS: CALIFORNIA BEARING RATIO ON SOIL CLASSIFICATION PROPERTIES - PROBLEM NO. 4

Regression Equation	Std. Error	R^2
CBR = 15.14 -5.43logS	4.94	0.073
CBR = 33.38 -11.48logS -0.74w	4.56	0.223
CBR = 36.56 -10.27logS -0.94w -0.16G	4.31	0.313
CBR = 120.83 -12.20logS -0.88w -0.43G -45.25logFA	4.02	0.413
CBR = 92.32 -9.40logS -1.20w -0.41G -43.86logFA +21.73logPL	3.87	0.462
CBR = 133.79 -8.67logS -1.75w -0.37G -42.25logFA +21.15logPL -0.32γ_d	3.83	0.482
CBR = 151.90 -11.67logS -1.84w -0.43G -27.82logFA +20.89logPL -0.38γ_d -17.26logF	3.80	0.498
CBR = 142.86 -10.62logS -1.85w -0.41G -26.17logFA +20.79logPL -0.40γ_d -12.59logF -1.60logGI	3.82	0.500
CBR = 144.04 -10.50logS -1.84w -0.40G -26.31logFA +20.62logPL -0.41γ_d -12.17logF -1.53logGI -0.69logPI	3.84	0.501
CBR = 150.55 -9.81logS -1.94w -0.40G -31.74logFA +15.06logPL -0.40γ_d -7.44logF -1.71logGI -4.10logPI +0.18LL	3.86	0.504

TABLE 25e. C-HORIZON REGRESSION RESULTS: CALIFORNIA BEARING RATIO ON SOIL CLASSIFICATION PROPERTIES - PROBLEM NO. 5

Regression Equation	Std. Error	R^2
CBR = 9.93 -2.70logG	4.75	.046
CBR = 43.83 -4.91logG -28.61logw	4.26	0.150
CBR = 53.74 -4.24logG -47.90logw +0.66PL	4.05	0.253
CBR = 65.10 -3.56logG -50.51logw +0.55PL -5.23logS	3.98	0.365
CBR = 131.44 -2.99logG -73.21logw +0.52PL -5.73logS -0.34γ_d	3.92	0.410
CBR = 126.75 -3.12logG -77.38logw +0.47PL -5.66logS -0.33γ_d +6.02logLL	3.94	0.421
CBR = 105.03 -2.70logG -79.63logw -0.06PL -4.97logS -0.45γ_d +43.57logLL -0.65PI	3.86	0.457
CBR = 105.63 -2.74logG -79.35logw -0.09PL -4.95logS -0.46γ_d +44.62logLL -0.66PI -0.50logGI	3.89	0.481
CBR = 107.05 -2.50logG -81.70logw -0.09PL -4.51logS -0.49γ_d +45.50logLL -0.69PI -1.34logGI +0.06FA	3.91	0.488
CBR = 109.25 -2.54logG -81.84logw -0.11PL -4.67logS -0.50γ_d +46.26logLL -0.70PI -1.12logGI +0.07FA -1.54logF	3.94	0.488

TABLE 26a. NONPLASTIC SOILS REGRESSION RESULTS: CALIFORNIA BEARING RATIO ON CLASSIFICATION PROPERTIES - PROBLEM NO. 1

Regression Equation	Std. Error	R^2
$CBR = 39.24 - 0.43FA$	9.21	0.136
$CBR = 74.99 - 0.44FA - 0.31\gamma_d$	9.10	0.180
$CBR = 80.82 - 0.35FA - 0.40\gamma_d + 0.06G$	9.20	0.183
$CBR = 99.45 - 0.28FA - 0.54\gamma_d + 0.09G - 0.46w$	9.32	0.186
$CBR = 97.40 - 0.25FA - 0.54\gamma_d + 0.10G - 0.46w - 0.02F$	9.46	0.185
$CBR = 1538.62 - 0.27FA - 0.53\gamma_d - 14.31G - 0.53w - 14.42F - 14.39S$	9.58	0.189

TABLE 26b. NONPLASTIC SOILS REGRESSION RESULTS: CALIFORNIA BEARING RATIO ON CLASSIFICATION PROPERTIES - PROBLEM NO. 2

Regression Equation	Std. Error	R^2
$\log CBR = 1.436 - 0.008F$	0.203	0.216
$\log CBR = 1.591 - 0.006F - 0.005FA$	0.204	0.232
$\log CBR = 2.643 - 0.001F - 0.010FA - 0.008\gamma_d$	0.203	0.257
$\log CBR = 3.255 - 0.000F - 0.012FA - 0.012\gamma_d - 0.014w$	0.205	0.262
$\log CBR = 3.752 - 0.005F - 0.004FA - 0.015\gamma_d - 0.022w - 0.003S$	0.207	0.268
$\log CBR = 20.140 - 0.169F - 0.005FA - 0.015\gamma_d - 0.023w - 0.116S - 0.164G$	0.210	0.269

TABLE 26c. NONPLASTIC SOILS REGRESSION RESULTS: CALIFORNIA BEARING RATIO ON CLASSIFICATION PROPERTIES - PROBLEM NO. 3

Regression Equation	Std. Error	R^2
$\log CBR = 2.27 - 0.61 \log FA$	0.213	0.137
$\log CBR = 8.72 - 0.72 \log FA - 3.06 \log \gamma_d$	0.202	0.248
$\log CBR = 11.29 - 0.71 \log FA - 4.02 \log \gamma_d - 0.58 \log w$	0.203	0.260
$\log CBR = 15.30 - 0.89 \log FA - 5.67 \log \gamma_d - 0.95 \log w + 0.07 \log F$	0.203	0.280
$\log CBR = 12.70 - 1.06 \log FA - 4.57 \log \gamma_d - 0.75 \log w + 0.09 \log F + 0.21 \log S$	0.205	0.286
$\log CBR = 12.56 - 1.07 \log FA - 4.55 \log \gamma_d - 0.76 \log w + 0.09 \log F + 0.28 \log S + 0.02 \log G$	0.208	0.289

TABLE 26d. NONPLASTIC SOILS REGRESSION RESULTS: CALIFORNIA BEARING RATIO ON CLASSIFICATION PROPERTIES - PROBLEM NO. 4

Regression Equation	Std. Error	R^2
$CBR = 63.48 - 26.01 \log FA$	9.23	0.133
$CBR = 117.14 - 30.04 \log FA - 0.42 \gamma_d$	8.94	0.208
$CBR = 140.67 - 36.64 \log FA - 0.55 \gamma_d + 2.47 \log F$	8.97	0.224
$CBR = 179.58 - 39.47 \log FA - 0.77 \gamma_d + 3.54 \log F - 0.87 w$	9.04	0.234
$CBR = 162.62 - 43.50 \log FA - 0.67 \gamma_d + 3.94 \log F - 0.71 w + 5.17 \log S$	9.16	0.236
$CBR = 162.31 - 43.53 \log FA - 0.67 \gamma_d + 3.94 \log F - 0.71 w + 5.34 \log S + 0.04 G$	9.30	0.236

TABLE 26e. NONPLASTIC SOIL REGRESSION RESULTS: CALIFORNIA BEARING RATIO ON CLASSIFICATION PROPERTIES - PROBLEM NO. 5

Regression Equation	Std. Error	R^2
$CBR = 39.24 - 0.43FA$	9.21	0.216
$CBR - 75.00 - 0.44FA - 0.31\gamma_d$	9.10	0.232
$CBR = 90.22 - 0.56FA - 0.43\gamma_d + 2.51\log F$	9.14	0.257
$CBR = 126.65 - 0.58FA - 0.57\gamma_d + 3.21\log F - 17.98\log w$	9.24	0.262
$CBR = 118.58 - 0.63FA - 0.52\gamma_d + 3.55\log F - 14.60\log w - 0.79\log G$	9.35	0.268
$CBR = 153.76 - 0.56FA - 0.67\gamma_d + 3.16\log F - 21.25\log w - 1.07\log G - 7.14\log S$	9.47	0.269